Skin temperature variations in the cold

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Skin Temperature Variations in the Cold

By

Damien Fournet

A Doctoral thesis submitted in partial fulfilment of the requirements for
the award of Doctor of Philosophy of Loughborough University
March 2013

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ABSTRACT

Skin temperature plays an important role in human thermoregulation together with core temperature. Skin temperature varies to a large extent across the body and this is especially pronounced in cold environments. The variations of skin temperature are also involved in the generation of regional thermal perceptions that can lead to behavioural adjustments. Whilst the temporal and inter-individual variations of skin temperature have been well studied using contact sensors, the knowledge of spatial variations has received less attention in the literature. Infrared thermography is a specific imaging technique particularly valuable for the exploration of the topography or pattern of skin temperature across the body. Most research using this technique has only been case studies or experiments focused on one specific body region. However, extensive regional skin temperature data over the whole-body can be proven useful for different types of applications including the sport clothing industry in combination with other body-mapping data.

The primary aim of this thesis was to develop an original and standardised method using infrared thermography enabling whole-body skin temperature data to be compared for the assessment of spatial, temporal and inter-individual variations. A specific methodology for infrared data collection and data processing was successfully developed in order to combine data from a variety of participants varying in anthropometrical characteristics. The main outcomes were the production of several skin temperature body maps, either absolute maps to show the magnitude of the temporal or inter-individual effects, and normalised maps (relative to mean skin temperature) allowing for topographical comparisons between protocol stages, populations or interventions.

The second aim of the thesis was to extend the understanding of the skin temperature patterns and how these could relate with thermal perceptions. The body-mapping method gave the opportunity to investigate a large amount of conditions, where various internal or external determinants of skin temperature were involved. This was mainly done in cool to cold environments (5°C to 20°C) where skin temperature is not uniform but is associated with local and overall comfort. Studies were firstly performed in semi-nude conditions (Chapter 3, 4, 5) and then in clothed conditions (Chapter 6 and 7). The semi-nude studies were designed to explore the potential sex-differences in regional skin temperature responses whilst running (Chapter 3) with a special interest in the role of skinfold thickness, this was further extended with a group of males at rest having a large variety of fat content and thickness (Chapter 4). The influence of exercise type and air temperature on skin temperature patterns was studied with a rowing exercise (Chapter 5). Studies were then performed in clothed conditions (Chapter 5, 6). The influence of real-life conditions on skin temperature patterns and associated perceptual responses was observed during a hiking scenario (Chapter 6). Following these descriptive studies, manipulation of skin temperature patterns was performed using clothing in order to determine the presence of any relevant effect on thermal comfort (Chapter 7).

Our results demonstrated that the skin temperature pattern over the whole-body is relatively universal with several features being consistently found regardless of the conditions or the populations. The upper body is usually warmer than the lower body and the body creases (orbital, elbow regions etc.) are also warmer than surrounding
regions. A Y-shape of colder temperatures has been highlighted over the anterior torso as well as a T- or Y-shape of warmer temperature over the posterior torso. There are yet some specificities that can be displayed due to active muscles during exercise such as the warmer skin overlying the trapezius and biceps muscles in rowing (Chapter 5), the influence of the backpack construction with up to 3°C warmer skin temperature in the lower back (Chapter 6) or the importance of additional clothing insulation minimizing the anterior Y-shape of colder skin temperatures (Chapter 7).

Beyond the thermal patterns, absolute skin temperature differences have been observed between sexes with females displaying 2°C colder skin during semi-nude running (Chapter 3) and 1°C colder skin during clothed walking (Chapter 6) compared to males. The skin temperature difference can also be as large as 6°C colder skin for an obese male compared to a very lean male (40% vs 7% body fat). Despite these differences, there were almost no significant differences in overall and regional thermal sensations and comfort between sexes or between males with varying body fat. Our results focused on body fat revealed that overall fat content and sum of skinfolds was inversely associated with the mean skin temperature response during various protocols (Chapter 4, 6. 7). Local skinfold thickness explained the inter-individual variability of local skin temperature for resting (Chapter 4) and exercising males (Chapter 7) in most body regions.

In terms of intra-individual variations, the distribution of skinfold thickness across the anterior torso explained the distribution of skin temperature in this segment solely in conditions with strong regional contrasts (Chapter 3, 4 and 7). When the whole-body skin temperature pattern is considered, our body-mapping approach failed to show relationships between skin temperature distribution across the body and regional skinfold thickness distribution neither at rest nor during exercise. The relative contribution of other internal determinants such as local heat production, local blood flow distribution and local anthropometry should be further investigated to fully elucidate the spatial skin temperature variations depending on the climate, clothing and the body thermal state.

Lastly, there was a trend towards improved thermal comfort during rest and exercise in the cold through a manipulation of skin temperature patterns targeting the naturally cold body regions with high insulation, therefore obtaining a more homogeneous skin temperature distribution across the body (Chapter 7).

The present work will benefit the sport goods industry. The descriptive results of skin temperature variations will be useful in order to validate multi-segmental model of human thermoregulation. Further work can include pattern predictions for exercise types and conditions not covered by the present thesis. The skin temperature maps will mainly feed the general body-mapping approach for clothing design taking into account several other body mapping data such as sweat mapping and the combination of cold, warm and wetness sensitivity mappings. Lastly, the present results have highlighted the interest for targeted solutions and also the need for more evolutive systems in the field of cold weather apparel.

**Keywords:** thermoregulation – skin temperature – infrared thermography – bodymapping – regional – thermal comfort – exercise – sex – body fat
# THESIS OVERVIEW

<table>
<thead>
<tr>
<th>Chapter</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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## Participants

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<tr>
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<tr>
<td>Males / Females</td>
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<td>7 sites</td>
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<tr>
<td>Males / Females</td>
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<th>60' rest - 30' cycle 100W</th>
<th>40' row 60% VO$_{2\text{,max}}$</th>
<th>60' walk (+15%) - 15' rest - 30' walk (-15%) 55% VO$_{2\text{,max}}$</th>
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<td>$T_a$</td>
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<td>5°C</td>
<td>5°C</td>
<td>5°C</td>
</tr>
<tr>
<td>rh</td>
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<td>semi-nude</td>
<td>semi-nude</td>
<td>backpack + overall garments (1.3 Clo)</td>
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## Measurements

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<td>Y</td>
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<td>Subjective evaluation</td>
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<td>6 stages</td>
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<td>6 stages</td>
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STATEMENT

The work presented in this thesis was part funded by both the Environmental Ergonomics Research Centre (Loughborough Design School formerly Department of Human Sciences) and Oxylane Research, the research & development department of Oxylane (France). The data collected and the methodology developed in this thesis have been used by the research teams for the development of sport products ensuring the maximisation of thermal comfort, well-being and safety of active people.

The study presented in Chapter 3 was conducted jointly with Miss Lindsey Ross in the context of her BSc. dissertation work. The author designed the experiment, trained the student on the methodology, collected the data with the student (author on male participants and Miss Lindsey Ross on female participants), and provided her with co-supervision. The data analysis presented in this thesis was independently done by the author.

The study presented in Chapter 5 was conducted jointly with Mr Mark Williams. The author assisted in the supervision of the student during his BSc. dissertation work and was responsible for the design of the experiment. The author trained the student on the methodology and provided guidance during data collection. The raw data were re-analysed for inclusion in this thesis.

The studies presented in Chapter 4 and Chapter 6 were performed with the help of Miss Katy Griggs, research assistant in the Environmental Ergonomics Research Centre, who provided support in the recruitment phase and conducted data collection jointly with the author. The study presented in Chapter 7 was performed solely by the author.
Acknowledgements

First and foremost, I would like to thank my supervisor, Professor George Havenith, for guiding my path throughout the journey with his knowledge, trust and kindliness. He made this experience very fruitful and I will be forever grateful for the support and opportunities he has given me.

I would like to thank every single person I have met at the Environmental Ergonomics Research Centre in Loughborough, making this place such a fantastic environment for research and the source of great friendships. A special thank is due to Miss Katy Griggs for her amazing assistance, to Dr Simon Hodder and Miss Jane Purvey for their help and good mood, and to Dr Yacine Ouzzhara and Dr Nicola Gerrett for sharing so many memorable scientific and social experiences.

I would also like to acknowledge the people at Oxylane Research in Lille for welcoming me in the enthusiastic and challenging environment of Oxylane. Particular thanks to my wonderful colleagues of the Thermal Comfort team for being so kind and supportive. I would like to say a special thank you to Dr Jeremy Cornolo, Dr Sophie Herpin, Mr Thomas Voelcker and Dr Bernard Redortier for their guidance and invaluable advice from the start to the end of the journey, making the link between fundamental and applied research so exciting.

Finally, I would like to thank all my friends and family. This long journey started with a single step; they have given me the confidence to dare take that step but also every other in the darkest or brightest days on the path. Je remercie enfin mes parents du fond du cœur pour leur présence sans faille à mes côtés et leur amour qui m’a permis d’oser cette aventure inoubliable.
Publications & Presentations

**Journal papers**
  *related to Chapter 3*
  *related to Chapter 2*

**Conference papers**

**Conference poster presentations**
  *First prize for best poster presentation*


  *Young Investigator Award*
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CHAPTER 1
Introduction and Review of Literature

Introduction

The skin covers the whole human body and is by far the largest organ. In many ways, it allows humans to interact with their environment. The temperature of the skin is crucial for effective thermoregulation, together with the temperature of inner organs and the brain. Skin temperature (T_{sk}) is strongly interconnected with core temperature (T_{core}) which is the most important regulated variable for the survival of human homeotherms. Thermal afferents coming from the skin contribute to the unconscious maintenance of T_{core} within a narrow range as well as the conscious perception of the environment.

T_{sk} varies over the body surface, and from early research it was apparent that the variations of local T_{sk} were larger in colder environments (Pembrey, 1898). The thermoregulatory system therefore receives a large variety of peripheral information. In cold environments, T_{sk} also greatly contributes to thermal discomfort (Benzinger, 1963). Although the distribution of T_{sk} over the body has been investigated in various environments and activities (Werner and Reents, 1980), the knowledge of T_{sk} intra-segmental or spatial variations (i.e topography) has received only little attention in the literature.

Considering the importance of T_{sk} for both thermoregulation and comfort, the present work was focused on the understanding of T_{sk} topography over the whole-body. This was directed towards a special interest in improving the skin-clothing-environment system for thermal comfort, especially during exercise in the cold. This chapter will provide important insights in the measurements of T_{sk} throughout history, with an emphasis on the best way to investigate its topography over the body (T_{sk} mapping). The regulatory and perceptual significance of T_{sk} will also be presented as well as the basics of heat exchanges at the skin. Lastly, the external and internal determinants of T_{sk} affecting these heat exchanges will be discussed.
1.1. The measurement of skin temperature

The first thermometer was developed by Galileo Galilei around 1600 and Santorio Santorio was the first to adapt it for $T_{\text{core}}$ measurements in 1612 (Ars de Medicina Statica). Gabriel Farenheit introduced the first mercury thermometers in 1724 and various scales were adapted to measure temperature (by Réaumur, Anders Celsius, Lord Kelvin). From these first developments, thermometers were then used for medical applications to monitor $T_{\text{core}}$ at the mouth, axilla, rectum or urine. Pembrey (1898) reported that the investigation of $T_{\text{sk}}$ had been largely neglected. From the 19th century, various instruments were created to overcome the challenges of surface $T_{\text{sk}}$ measurement with a distinction between contact and non-contact methods.

1.1.1. Contact measurements

The first reported measurement of $T_{\text{sk}}$ was made by Davy in 1814 holding a bulb mercury thermometer against the skin (Burton, 1934). He later used flat bulb mercurial thermometers in order to reduce the interference of the surrounding environment. Using flat thermometers, Pembrey (1898) performed measurements at different times of day and in various situations (at rest, in bed, after walking). He highlighted the considerable variations of $T_{\text{sk}}$ across the body with a clear distinction between clothed and unclothed body parts.

During the same period, scientists developed less convenient but more accurate technique with thermo-electric measurements. Thermocouples were created using copper-constantan junctions (one in a reference bath, one applied to the skin) and measuring the deflection of a string galvanometer. Benedict, Kunkel, Aldrich and many others performed extensive observations of $T_{\text{sk}}$ with thermocouples at the end of 19th / beginning of the 20th century. Benedict et al. (1919) were the first to report a temperature curve describing $T_{\text{sk}}$ across different body regions (Figure 1.1).
Figure 1.1. Photographic records from a string galvanometer for skin temperature over the front and back body of a nude resting male following 2 ½ hour exposure at 15°C. From Benedict et al. (1919)

Although the use of thermocouples provided an initial insight into $T_{sk}$ variation, the potential sources of errors of these contact probes due to calibration, manipulation error (reliability of the contact) and effect of the instrument on the skin were later emphasized (Hardy, 1934).

Burton (1934) introduced the gauze resistant jacket in order to measure $T_{sk}$ over an extended area of the body. He explored the $T_{sk}$ responses at the chest and posterior leg during exercise on a cycle ergometer.

Thermistors have also been used for physiological studies. Their construction incorporates a piece of ceramic with a known resistance that fluctuates with temperature. Depending on its size, the thermistor usually has a longer response time compared to thermocouples. Several issues have been reported pertaining to the use of thermistors and thermocouples such as the influence of shape and contact pressure (Jirak et al., 1975), the additional covering to hold the sensor onto the skin (Molnar and Rosenbaum, 1963; Psikuta et al., 2013) and some practical limitations especially during exercise such as entangled wires or sensors falling off (Buono et al., 2007).

In the 2000’s, another type of contact sensor became available for thermophysiological studies: the Thermocron iButton. This small self sufficient system (16x6mm$^2$) has a semiconductor temperature sensor that measures and records temperature in a protected memory section for post-test download. The reliability of Thermocron iButtons has been validated for human $T_{sk}$ measurements with the great advantage of having no obtrusive wires. The main drawback of this sensor type is related to having a slow response time (van Marken Lichtenbelt et al., 2006; Harper-Smith et al., 2010), the variations induced by the attachment method (Psikuta et al., 2013) and the absence of real time data visibility.

The measurement of local $T_{sk}$ by contact sensors is decisive for the calculation of mean skin temperature ($\bar{T}_{sk}$) which is commonly used as an indicator of the thermal
stress (Frim et al., 1990). $\bar{T}_{sk}$ can also be used to estimate total body heat content when direct calorimetry is not available. Since the 1930’s, several $\bar{T}_{sk}$ calculation equations have been created based on 3 to 15 local $T_{sk}$ measurements (Choi et al., 1997). However, the exact position of the contact sensors is usually poorly defined in the different equations. It is also assumed that each location best represents the average temperature of the region whereas point-to-point variation in local $T_{sk}$ can vary by as much as 7°C over 5 cm (Frim et al., 1990).

Despite these limitations, contact measurements remain the most common way of exploring the thermal responses to various environments and activities. Using thermocouples, Werner et al. (1980, 1985, 1988) have undoubtedly contributed to the knowledge of $T_{sk}$ distribution, performing extensive measurements under different thermal and work loads. They observed that $T_{sk}$ topography changed only to a small extent in exercising subjects compared to a resting state. As highlighted in early investigations (Pembrey, 1898), the $T_{sk}$ difference between body regions could be as large as 10°C in a cold environment (Figure 1.2).

![Figure 1.2](Figure removed due to copyright)

**Figure 1.2** Topography of body temperatures of a resting (A) and exercising (B) subject based on point measurements with thermocouples. From Werner et al. (1985)

Based on other simultaneous measurements and anatomical data, Werner and Buse (1988) have further improved models of human thermoregulation with spatially distributed parameters. They suggested the need for higher resolution in the temperature profiles and the consideration of the influence of clothing among other factors. The present work was designed to bridge this specific gap.

Overall, contact sensors are limited to the measurement of isolated points and they can not be used to precisely map $T_{sk}$ topography of extensive body regions. Increasing the resolution of $T_{sk}$ mapping would require other types of devices.
1.1.2. Non-contact measurements

Non-contact techniques are based on the principle that any object at a temperature above absolute zero (-273°C) emits energy at its surface in the form of a spectrum of electromagnetic waves of differing wavelengths and intensities (Williams, 1964). In 1800, Sir William Herschel discovered infrared radiation beyond the visible spectrum (> 0.8 µm). The emission spectrum of the skin is almost the same as a blackbody between 3 and 15 µm (Hardy, 1934) and its peak emission occurs at a wavelength of around 10µm according to Wien’s displacement law. The skin is an almost perfect absorber and, accordingly, a near perfect emitter. $T_{sk}$ could therefore be measured by determining the amount of infrared radiation coming from its surface (Williams, 1964).

Because radiation can be measured at a distance, scanning devices were developed to represent temperature contours of large surfaces in a pictorial form (Williams 1964). The name “Infrared thermography” (IRT) corresponds to the technique used by all these heat scanning devices and the outcome (i.e. thermal image) is named “thermogram”.

The first ever thermogram was recorded by Sir John Herschel, son of Sir William, in 1840 by evaporography where a layer of volatile liquid evaporates from a darkened membrane in a vacuum chamber (Ring, 1990). In the first part of the 20th century, accurate systems were constructed for military and space applications with different types of infrared detectors. In 1957, Ray Lawson was one of the first to use IRT clinically for the detection of breast cancer. Several improvements were made in the detectors (from temperature sensitive to cooled photosensitive detectors), faster scanning time and improved image recordings (Williams, 1964). The main objectives were to obtain high spatial sensitivity (small temperature differences between adjacent parts of the body) and to map a body region in a short time. A study by Vegthe and Solli (1962, cited in Barnes 1963) was among the first human investigation mapping $T_{sk}$ over the entire body.
In the 1960’s and 1970’s, IRT was extensively used for the measurements of abnormalities due to vascular and bone diseases or tumours (Barnes 1963, Williams 1964). The use of this technique as a diagnostic tool was promising but the clinical expectations were never realised due to its inaccuracy at the time (Ring, 1990).

In the field of thermal physiology, Veghte (1965) performed a large number of tests to determine the influence of various ambient temperatures (4, 23, 27°C) on regional $T_{sk}$ using 15 nude subjects. Cena and Clark (1976) indicated that IRT was only scarcely used in this field and even less for exercise physiology, during the 1970’s, 80’s and 90’s due to the high cost and difficulties in evaluating thermograms (Jirak et al., 1975). However, developmental work continued on this technique with Clark et al. (1977) publishing the first colour infrared thermograms of two exercising subjects (Figure 1.4).
Since the study by Clark et al. (1977), no experiments have reported whole-body thermograms during or following exercise. Most studies have focused on specific body parts to understand regulatory mechanisms between heat loss and heat production (Veghte et al., 1979; Goss et al., 1988; Hunold et al., 1992; Zontak et al., 1998; Ferreira et al., 2008; Merla et al., 2010). Some of these studies have performed quantitative analysis based on specific regions of interest in the thermograms but none of them have considered the thermal pattern over the whole body. The present work was aimed to extend the knowledge specifically on the thermal patterns in various conditions.

Nowadays, the use of IRT still remains limited although the spatial resolution of infrared camera has largely improved (up to 1280x1024 pixels) and their price has become much more affordable. However, infrared measurements are still impossible under clothing and continuous recordings are difficult in practice for reliable quantitative analysis. Processing time of the numerous thermograms is also one of the main drawbacks as indicated by McIntyre (1980). Current infrared cameras usually offer a relatively low absolute temperature accuracy compared to contact sensors (in general ±2°C vs ±0.1°C) but this can be compensated for by adequate calibration. On the other hand, they have particularly high spatial sensitivity (±0.1°C pixel to pixel) which make them very suitable for mapping large surfaces.

In summary, this section provided an overview of contact and non-contact methods from the origins of $T_{\text{sk}}$ measurements. Each of the measuring technique discussed are suitable for different research or clinical purposes as early research by Pembrey (1898) recognized. Recording large surface temperatures over the body is only possible with infrared thermography, and this non-contact method has some advantages over contact sensors which interfere with skin surface heat exchanges.

### 1.2. The role of skin temperature

The skin is the primary interface between the body core and the environment. It has both a protective and a sensory function. $T_{\text{sk}}$ can be sensed by peripheral thermoreceptors initiating unconscious (autonomic) and conscious (thermal comfort, behaviour) responses that will in turn adjust body temperatures. The main physical and physiological mechanisms involved in this regulation will be discussed in their interdependence with $T_{\text{sk}}$. 
1.2.1. Heat exchanges at the skin

A combination of four heat transfers can occur at the skin surface: conduction, convection, radiation and evaporation. They all conform to the laws of physics and contribute either to heat loss or heat gain. $T_{sk}$ relies on the balance of heat transfers within the body (from the body core to the skin) and towards the surrounding environment (from the skin to the environment).

**Conduction (K)** occurs between two solid surfaces by direct molecular contact. At the skin, contact can be created with clothing especially when pressed in a bed, a chair or between bare hands and objects. On a nude standing person, only 3% of the body surface area is in contact with the floor (sole of the feet). In physical terms, it can be written as the following equation:

$$K = h_k (T_{sk} - T_{surface}) \text{ (W.m}^{-2}\text{K}^{-1}) \quad (1)$$

where $h_k$ = conductive heat transfer coefficient (W.m$^{-2}$ K$^{-1}$)

The conductive heat transfer depends on the thermal inertia of the material in contact with the skin (volume * thermal conductivity). Within the body, conduction also occurs between heat sources and the skin surface depending on the conductivity of the underlying tissues.

**Convection (C)** refers to the physical exchange of heat between the body and an adjacent moving medium (air, water, blood). To characterize convective heat loss at the skin to the surrounding air, the equation is:

$$C = h_c (T_{sk} - T_a) \text{ (W.m}^{-2}\text{)} \quad (2)$$

where $h_c$ = convective heat transfer coefficient (W.m$^{-2}$ K$^{-1}$)

A relatively thick layer of heated air lies adjacent to the skin surface when there is no motion over the skin. Overall and regional convective heat transfer coefficients have been assessed on a nude thermal manikin by deDear (1997) in still-air and moving-air. For the whole body, standing in a uniform wind, Kerslake (1972) defined the coefficient as:

$$h_c = 8.3 \sqrt{v} \text{ (W.m}^{-2}\text{K}^{-1}) \quad (3)$$

where $h_c$ = convective heat transfer coefficient, $v$ = air velocity (m.s$^{-1}$)

The motion of the body itself during exercise can cause air motion across the skin surface. For a running person, the convective heat loss can be twice larger than obtained with the previous formula, e.g. at 4.5 m.s$^{-1}$, $h_c$ is equal to 30 W.m$^{-2}$K$^{-1}$
(Clark and Edholm, 1985). The continual replacement of warmed air by cooler air caused by body movements and the environmental air flow is called *forced convection*.

Moreover, from the body core to the skin surface, the cutaneous blood supply can greatly vary modifying the convective heat transfers within the body. This will be further discussed in 3.1.1.

**Radiation (R)** corresponds to the radiant energy emitted by a medium that is solely due to the temperature of the medium. This energy coming from the skin is captured by the thermal camera as previously presented (1.2). For application within a limited temperature gradient, it can be written as:

\[
R = h_r \varepsilon (T_{sk} - T_r) \text{ (W.m}^{-2}\text{)} \tag{4}
\]

where \(h_r\) = radiative heat transfer coefficient (W.m\(^{-2}\).K\(^{-1}\)), \(\varepsilon\) = emissivity of the skin (\(\varepsilon = 0.98\}; Steketee 1973), \(T_r\) = radiant temperature of the surrounding surfaces.

DeDear (1997) evaluated the overall and regional \(h_r\) for a nude manikin in still-air. This coefficient depends on the projected area of the body which is around 0.73 for a standing person (Fanger, 1967). In cold weather, radiative heat loss dominates but local heat gain can also occur from an external heat source.

The combination of convective and radiative heat loss is called *dry heat loss*.

**Evaporation (E)** depends on the water vapour pressure difference between the skin and the ambient air. Heat is lost from the evaporation of moisture present on the skin surface.

\[
E = h_e w (P_{sk} - P_a) \text{ (W.m}^{-2}\text{)} \tag{5}
\]

Where \(h_e\) = evaporative heat transfer coefficient (W.m\(^{-2}\).kPa\(^{-1}\)), \(w\) = skin wettedness (dimensionless), \(P_{sk}\) = water vapour pressure at the skin (kPa), \(P_a\) = water vapour pressure of the ambient air (kPa).

Moisture on the skin surface can stem from sweating, especially activated during exercise, but also from some insensible water loss at the skin. Respiratory heat loss also occurs by a combination of dry and evaporative heat loss with inhaled air typically being both heated and moistened before exhalation. The respiratory heat loss can be written as follows (Fanger, 1970):

\[
C_{res} + E_{res} = [0.00014 M (34 - T_a) + 0.0173 M (5.87 - P_a)] \text{ (W.m}^{-2}\text{)} \tag{6}
\]

Where \(M\) = metabolic heat production (W.m\(^{-2}\))
Evaporative heat loss becomes the main avenue of heat loss when $T_a$ is close to $T_{sk}$. The addition of clothing will necessarily impede dry and evaporative heat losses depending on its thermal properties as discussed in 3.2.3.

The value of $T_{sk}$ is a resultant of the combined influence of four types of heat transfers (conduction, convection, radiation and evaporation). The adjustment of these physical processes according to physiological and environmental factors will be presented in section 1.3.

**1.2.2. The signalling role of skin temperature**

**1.2.2.1. Thermoreception**

*Thermoreception* refers to the sensory capacity of the skin to detect the temperature of the environment and the body. $T_{sk}$ varies depending on the balance of the various heat transfers and this thermal signal can be detected by cutaneous receptors. Thermal stimuli are sensed by free-nerve endings (un-encapsulated) located at a depth of approximately 200 $\mu$m beneath the skin surface in the dermis at the limit with the epidermis (Schiffman, 2001). Cutaneous thermoreceptors are found at these free nerve endings with a specific morphology (peptide content, intracellular and surface antigens) respective to the type of stimuli detected (warm or cold) (Willis, 2004). In general, there are about ten times more cold receptors than warm receptors in the skin with cold receptors located close to the surface and warm receptors at deeper levels (Schiffman, 2001). They are non-uniformly distributed over the body as described by mapping studies (Rein, 1925; Strughold and Porz, 1931).

**1.2.2.2. Signal transduction**

The mechanism of *transduction* corresponds to the conversion of the thermal signal into an electrical action potential. It occurs in specific ion channels of the Transient Receptor Potential (TRP) family (expressed by the free nerve endings) that respond to temperature stimuli of distinct threshold values (Schepers and Ringkamp, 2010). Hensel (1981) identified that the firing rate of thermoreceptors depends not only on static temperature but also on the rate of change of temperature. The dynamic receptor response is larger than the static response, with a peak discharge rate before a return to steady-state level. Cold thermoreceptors respond to steady-state
temperature from 5 to 40°C (peak discharge rate at 25°C) and also above 45°C in the noxious range. Warm thermoreceptors are mainly active at temperatures from 29°C to 45°C (peak discharge rate at 42°C). At the normal resting $T_{sk}$ of 33°C in thermoneutral environment, cold receptors are more active than warm receptors (Hardy and Hoppel, 1938; Guyton and Hall, 2000).

1.2.2.3. Signal transmission

Specific neuronal afferents are responsible for the transmission of the thermal signal. Afferent fibres from thermoreceptors are commonly dichotomized into the $A\delta$ myelinated axons for cold receptors and $C$ fibres for warm receptors (Spray, 1986). The fibres impulse has a constant voltage of some 50 mV and a propagation velocity of 5 to 30 m.s$^{-1}$ ($A\delta$ fibres) and 0.5 to 2 m.s$^{-1}$ ($C$ fibres). Afferents from cold and warm receptors synapse with the second order neurons in the dorsal horn of the spinal cord. The axon of these neurons cross the midline and ascend in the lateral spino-thalamic tract (Spray, 1986). The thermal signal follows this neuronal pathway in the afferent branch of the autonomic nervous system before reaching the hypothalamus in order to be integrated.

1.2.2.4. Signal integration

Warm signals reach the anterior aspect of the hypothalamus whereas cold signals reach the posterior aspect of the hypothalamus and the pre-optic region (Benzinger, 1963). There are some crossed inhibitory connections between the warm and cold systems (McIntyre, 1980). $T_{sk}$, via the thermoreceptors, is not the only thermal signal being integrated at this cortical level. The hypothalamus also receives temperature signals from central thermoreceptors located in core body sites such as the medulla, spinal cord, blood vessels, abdominal cavity as well as within the hypothalamus itself (Hensel, 1981).

Thermal signals are not only integrated in the hypothalamus but also in higher cortical centers to elicit conscious thermal responses responsible for thermal behaviour. The full localization, discrimination, and interpretation of the signal require processing in the somato-sensory cortex (parietal lobe). The sensory information can be conveyed directly or via thalamus projections and midbrain nuclei to the cortex. Benzinger (1963) demonstrated that the afferent fibres from cutaneous cold receptors for conscious cold sensation bypass the posterior
hypothalamic synapses and are therefore not inhibited by central-warm reception. Studies using functional magnetic resonance imaging have demonstrated projections of the thermal signals into the insula, primary and secondary orbitofrontal and cingulated cortices for thermal sensations (Davis et al., 1998) and in the amygdala for cold discomfort (Kanosue et al., 2002). These cortical regions correspond to the phylogenetically ancient areas of the brain that are similarly activated by pain, thirst or hunger (Egan et al., 2005).

In summary, $T_{sk}$ and its rate of change determine the firing rate of cutaneous thermoreceptors. Thermal signals from cutaneous thermoreceptors are then integrated with signals from central receptors to initiate compensatory thermoregulatory response that maintain $T_{core}$ within a narrow range. This is effectively driven by efferent autonomic mechanisms (1.2.3) and/or adjustment of individual behaviour (1.2.4).

1.2.3. Autonomic regulation

The autonomic nervous system controls involuntary regulatory functions of the human body (respiration, digestion, thermoregulation etc.). Studies have shown that temperature regulation is primarily achieved by cutaneous cold reception and central warm reception and that central cold reception and peripheral warm reception played secondary roles (Mekjavic and Eiken, 2006). This section will provide a general overview of the different thermo-effectors or descending signals of the autonomic thermoregulatory system.

1.2.3.1. Human heat balance

Human thermoregulation actively enables the maintenance of $T_{core}$ through a complex system of thermal receptors and effectors as well as the contribution of non-thermal factors. The temperature of central regions, which contains vital organs, is determined by the balance between heat production and heat loss. An increase in $T_{core}$ is usually associated with positive heat storage within the body. The human heat balance equation can be written as follows:

$$S = M - W - E - K - C - R$$  \hspace{1cm} (7)

where $S = $ net heat storage ($W.m^{-2}$), $M = $ metabolic heat production ($W.m^{-2}$), $W = $ external work performed ($W.m^{-2}$, positive or negative), $E = $ evaporative heat loss
(W.m$^{-2}$), $K =$ conductive heat transfer (loss or gain) (W.m$^{-2}$), $C =$ convective heat transfer (loss or gain) (W.m$^{-2}$), $R =$ radiative heat transfer (loss or gain) (W.m$^{-2}$).

The different physical heat transfers that passively affect the human body ($conduction$, $convection$, $evaporation$ and $radiation$) have been previously described (2.1).

Metabolic heat ($M$) is continually produced within the body by active tissues. The metabolic rate can vary from 50 to 60 W.m$^{-2}$ for a resting person to above 600 W.m$^{-2}$ during intense exercise. Mechanical efficiency ($\eta$) is the ratio between external work output ($W$) and metabolic heat production ($M$); it depends on the task and can vary with training. It is for most tasks close to 0% (no impact on the outside world) and can be as large as 25% in case of the work performed on a cycle ergometer. Negative work (such as downhill walking) adds up to the metabolic heat produced.

1.2.3.2. Main autonomic effectors and the role of skin temperature

Effector mechanisms of human thermoregulation are aimed towards actively modifying heat loss and heat production within the body. Four main autonomic mechanisms can be identified: $vasodilation$, $sweating$, $vasoconstriction$ and $shivering$. There is still some debate about the nature of the signal triggering these responses. The hypothalamus seems to act as a thermostat integrating the thermal signals from skin and central thermoreceptors and comparing these body temperatures to a reference signal. Depending on the model proposed, this reference signal can be represented as a single thermostat set-point or as a number of thresholds. The outcome of this comparison always leads to the initiation of thermo-effectors responses.

Small deviations from this reference signal can be compensated for by fine tuning of the vasomotor tone, modifying the conductive and convective heat transfers to and from the skin surface. $Vasoconstriction$ refers to the constriction of smooth muscles around skin arterioles and superficial veins. This mechanism increases insulation of the skin and underlying tissues, therefore reducing heat loss to the environment. On the other hand, when body heat storage rises, $vasodilation$ increases the blood supply to the skin which favours heat loss to the environment through the concomitant increase of $T_{sk}$.

With larger deviations from the reference signal, the thermoregulatory system can trigger sweating or shivering. $Sweating$ prevents excessive rise in $T_{core}$ by removing
heat at the skin surface through evaporation of the water secreted by the eccrine sweat glands over the whole-body. *Shivering* prevents the drop of $T_{core}$ by the generation of additional heat through rapid and involuntary contractions of superficial muscles. Heat production in shivering can be 3 to 5 times larger than the basal metabolic rate (Toner *et al.*, 1986).

The posterior hypothalamus acts as the defence against cold with descending signals for *vasoconstriction* and *shivering*. On the other hand, the anterior hypothalamus governs the heat dissipation responses for *vasodilation* and *sweating*. Many interconnections and cross-inhibitions exist between these two controlling centers. The four mechanisms (*vasoconstriction*, *vasodilation*, *sweating* and *shivering*) will be discussed in section 3 as they can all induce changes in $T_{sk}$.

Several studies have attempted to quantify the relative contribution of $T_{sk}$ and $T_{core}$ in the magnitude of these effector responses. The contribution ratio ($T_{core} / T_{sk}$) vary from 6:1 to 20:1 for the sweating response (Nadel *et al.*, 1970; Wyss *et al.*, 1974), 3:1 to 5:1 for the shivering response (Mekjavic and Morrison, 1986; Cheng *et al.*, 1995) and around 3:1 for vasomotor changes (Frank *et al.*, 1999).

It is worth mentioning that some non-thermal factors such as exercise, blood glucose, hydration, plasma osmolality, sleep or fever also affect thermoeffectors for heat loss and heat production.

### 1.2.3.3. Body temperatures during exercise

The heat produced during exercise strongly modifies body temperature values. The body can tolerate large deviations from the normothermic range of $T_{core}$ which varies from 36.1 to 37.8°C (Wunderlich 19th century cited in Weller, 2005). After a marathon, runners can sustain $T_{core}$ as high as 41°C with no life-threatening risks (Cheuvront and Haymes, 2001).

Depending on the environment, the avenues of heat loss would differ for the protection of $T_{core}$. In hot conditions, the small temperature difference between $T_{sk}$ and ambient temperature ($T_{a}$) impedes dry heat loss and evaporative heat loss becomes crucial. During semi-nude exercise in a cold environment, dry evaporative heat loss represents approximately 75% of the total heat loss, the remaining 25% is represented by evaporative heat loss (Nielsen *et al.*, 1938). For moderate to high intensity exercise, a rise in $T_{core}$ would likely occur even in cold environments with potentially low skin and muscle temperatures (Nimmo, 2004). In the cold, the low
T_{sk} (peripheral cold reception) can partly inhibit sweating caused by an exercise-induced rise in T_{core} (central warm reception) (Robinson et al., 1949). This demonstrates the interconnections between the hypothalamic regulating centers. Despite different avenues for heat loss, the rise in T_{core} will be independent of T_{a} as opposed to the T_{sk} response. The work rate or exercise intensity will determine whether the heat production offsets the heat loss, and consequently T_{core}. Walking at 5 \text{ km.h}^{-1} (30\% \text{ } VO_{2,\text{max}}) in a 5°C environment can be sufficient to maintain T_{core} for up to 5-6 hours (Weller et al., 1997). On the other hand, T_{sk} is little affected by the work rate and this has been shown for T_{a} between 10°C and 30°C (Gagge et al., 1969).

The optimal conditions for a prolonged exercise performance (run at 70\% \text{ } VO_{2,\text{max}} or completion of a marathon) have been reported to be around 10-12°C T_{a} (Galloway and Maughan, 1997; Ely et al., 2007). Recently, Sawka et al. (2012) have demonstrated that high T_{sk} (> 35°C), not a high “critical” T_{core}, could be the primary factor impairing submaximal exercise performance. These studies highlighted the role of T_{sk} for exercise performance and suggest the potential benefits of lowered T_{sk}. Extensive cooling of the skin can yet be detrimental for muscular performance mainly in sprinting conditions through several mechanisms such as reduced nerve conduction velocities, reduced excitability of the motoneuronal pool etc. (Meigal et al., 1998, Heus et al., 1995).

Although the combination of heat exposure and exercise imposes some challenges on the thermoregulatory system, it is generally acknowledged that humans are tropical animals with a very effective system for the prevention of overheating (McIntyre, 1980). On the other hand, the defence against cooling is relatively weaker and it is behavioural responses that allow man to live in a cold climate.

1.2.4. Thermal perceptions and behavioural regulation

1.2.4.1. Definitions

Behavioural temperature regulation refers to any coordinated action establishing a preferred condition for heat exchange between the environment and the body (heat loss, heat gain or heat balance) (IUPS Thermal Commission, 2001). Together with
autonomic thermoregulatory processes, they define the whole range of physiological
temperature regulation. The complex pattern of somato-motor activities that serve as
behavioural thermoeffector responses involve a wide range of actions (e.g. moving to
a different thermal ambiance, change in posture, wetting of body surfaces, changes of
microclimate by nest building, huddling) and it also includes voluntary exercise and
cultural achievements (clothing, housing, air conditioning, etc.) (IUPS Thermal
Commission, 2001). The various voluntary behavioural actions are closely related to
the psychological expressions of an individual thermal state. Thermal sensation
relates to how a person “feels” and not how the environment may be described
(Parsons, 2003). Thermal comfort can be defined as a subjective indifference to the
thermal environment (IUPS Thermal Commission, 2001). This definition does not
correspond to a judgement of a personal thermal state and would be more applicable
to building environment. Clark and Edholm (1985) reported that in a state of thermal
comfort, a person is generally unaware of any temperature sensation and there are no
parts of the body feeling either too hot or too cold. For the present work, a definition
that clearly integrates both the internal and environmental components in a personal
judgement of thermal comfort is more suitable. As indicated by Zhang and Elander
(1997), comfort and discomfort can be seen as two different entities in ergonomics
(especially in the interaction with objects) and aesthetics can play a determining role.
When studying the thermal side only of comfort, biomechanical and aesthetical
aspects are clearly eliminated and thus favour a definition of thermal comfort as an
absence of thermal discomfort.

1.2.4.2. Overall mechanisms

With a psychological basis, Auliciems (1981) has conceptualised the connection
between thermal judgements (sensation and comfort) and behavioural actions with an
integration of inputs from past experiences and personal expectations (Figure 1.5).
Similar to autonomic regulation, the afferent thermal signals integrated for the
production of thermal judgements and eventually for behavioural regulation are
coming from the cutaneous and deep thermoreceptors. The neuronal pathways have
been previously described in 1.2.2.

The exact conscious process that leads to actions is not fully understood. As changes
in body temperatures undoubtedly manifest as perceptual changes, the initiation of a
conscious thermo-behavioural response would probably not occur without thermal
perception (Chatonnet and Cabanac, 1965). Some authors indeed postulated that thermal discomfort drives behavioural thermoregulation, while thermal sensation initiates autonomic thermoregulatory responses (Gagge et al., 1967; Taylor et al., 1995). Other psychological inputs with or without underlying physiological mechanisms (e.g. mood, hunger) may also interfere in the decisional process.

1.2.4.3. Skin temperature and perceptions

Many different studies have investigated the association between thermal comfort and body temperatures (\(T_{sk}\) and \(T_{core}\)). Ward (1930) cited the work of Kunkel (1889) and Rubner (1895) who reported that man in a state of comfort has \(\bar{T}_{sk}\) of 33 to 34°C,
and she found warm discomfort 35 to 36°C $\bar{T}_{sk}$ and cold discomfort at 31 to 32°C $\bar{T}_{sk}$. The observations by Winslow et al. (1937) established a link between warm discomfort and $T_{core}$ together with sweating rate. Cold discomfort was positively associated with $T_{sk}$ and this was later confirmed by Benzinger (1963) separating the influence of $T_{core}$ and $T_{sk}$.

Chatonnet and Cabanac (1965) were among the first to claim that thermal comfort was influenced by both peripheral and central temperatures. Contribution ratios for both thermal inputs ($T_{core} / T_{sk}$) in the modulation of thermal comfort have been proposed by researchers and varied from 4:1 to 1:1 (Bleichert et al., 1973; Frank et al., 1999). In transient resting conditions, thermal comfort may be predicted more accurately from knowledge of $T_{a}$ than from $T_{sk}$ and $T_{core}$ (Gagge et al., 1967).

1.2.4.4. Regional skin temperature, perceptions and behaviours

Little attention has been paid to exploring the distinction between local thermal responses and whole-body responses. The distribution of $T_{sk}$ in a state of thermal comfort has been described by Vegthe (1965) and Olesen & Fanger (1973). Veghte (1965) provided the $T_{sk}$ topography over the whole-body for cold and warm discomfort as obtained by infrared thermography.

Some studies have looked at the relative contribution of body regions to thermal discomfort or sensation mainly by applying regional stimuli (Crawshaw et al., 1975; Pellerin et al., 2004; Cotter et al., 2005; Nakamura et al., 2008, 2013). The different methodologies and clamping procedures prevent clear conclusions from being drawn. Zhang et al. (2010) developed a model of sensation for each local body segment in static or transient conditions. The static response is based on local $T_{sk}$ and $\bar{T}_{sk}$. The dynamic response depends on derivatives of local $T_{sk}$, $T_{core}$ and $\bar{T}_{sk}$. They then described the generation of overall sensation and overall discomfort based on local values taking into account the concept of alliesthesia. Cabanac (1972) coined the concept of alliesthesia to describe how a given stimulus can arouse pleasure according to the internal state of the body. In his classical study, hand $T_{sk}$ was voluntarily lowered in a state of hyperthermia and vice versa.

The interaction of thermal inputs with thermo-behavioural responses has been reviewed by Schlader et al. (2009). They provided evidence that $T_{sk}$ alone or in combination with $T_{core}$, is an important and preferred thermal input capable of
initiating *thermo-behaviour*. The decision to behave (changing rooms) has been found to be associated with local warm discomfort locally at the head in a 46°C environment and no specific regional cold discomfort in a 5°C environment (Schlader *et al.*, 2012).

### 1.2.4.5. Body temperatures, perceptions and behaviours during exercise

The role of body temperatures in thermal perception and behaviour has largely been described for resting conditions with specific applications in the building or the car environments. During exercise, the relative importance of overall and regional body temperatures is less known. Benzinger (1978) suggested a state of “mixed comfort” during exercise since the central nervous system is receiving simultaneous warm signal from the deep thermoreceptors and cold signals from the skin. The existence of strong thermal contrasts may occur especially in cold environments (greater core-to-skin gradient and larger range of $T_{sk}$ across the body). Fanger (1970) recognized the role of *local discomfort* for resting thermal comfort but this may also be crucial during exercise with the large regional contrasts. It is generally accepted that exercising subjects can tolerate lower $T_{sk}$ and greater evaporative heat loss (Gagge *et al.*, 1969; Olesen *et al.*, 1972). Some sweating becomes therefore acceptable but excessive sweating mainly drives warm discomfort providing that wetness on the skin increases (Mc Intyre, 1980). Overall, *thermal comfort* seems mainly driven by thermal sensations as well as an unclear moisture sensation which could be determined by thermoreceptors and tactile sensors (Havenith, 2003). There is no consensus about the best predictors of local thermal sensation during exercise, potentially local $T_{sk}$, and mean body temperature (Nielsen and Nielsen 1984; Gwosdow and Berglund, 1987). The inter-segmental sensitivities to cooling (Ouzzahra PhD thesis, 2012) and to moisture on the skin (Gerrett PhD thesis, 2012) have been recently studied to elucidate the regional mechanisms involved in the generation of discomfort during exercise.

During exercise, the adjustment of exercise intensity and therefore metabolic heat production is considered as a *thermoregulatory behaviour*. In cool environments, voluntary exercise usually allows subjects to achieve heat balance and attain thermal comfort (Caputa & Cabanac 1980). There is some evidence that $T_{sk}$ mediates the adjustment of exercise intensity and thus metabolic heat production in order to
control the rise in $T_{\text{core}}$ within the range of the body thermoregulation (Tatterson et al.; 2000, Marino et al., 2004). In agreement with the model of teleoanticipation (Ulmer 1996), $T_{sk}$ may act at the onset of exercise in pre-setting the conscious perception of exercise. The selection of initial work rate or the total exercise duration has been observed to be higher in situation of lowered initial $T_{sk}$ (Crewe et al., 2008; Schlader et al., 2009). Alternatively, the reduction of $T_{sk}$ by 1-2°C by menthol or a water perfused suit changed thermal perception but did not modify the pacing strategies during exercise in the heat (Barwood et al., 2011; Levels et al., 2012).

In summary, $T_{sk}$ depends upon heat transfers within the body and between the skin and the environment. It plays an important role for human thermoregulation together with thermal signals from $T_{\text{core}}$ sensed by deep and central sensors. This thermal signal is either integrated by the brain controller (hypothalamus) to initiate autonomic responses or by higher cortical centers to generate thermo-behavioural responses based on thermal sensations and discomforts. Figure 1.6 summarises the main receptors and effectors of the physiological temperature regulation system.

![Figure 1.6](image.png)

**Figure 1.6** Simplified schematic representation of autonomic and behavioural temperature regulation. From Havenith (2001b)
1.3. The determinants of skin temperature

Several factors influence $T_{sk}$ by acting on the heat exchanges (conduction, convection, radiation, evaporation) within the body and between the skin and the environment. A distinction between internal and external determinants has been suggested by Houdas et al. (1975).

External determinants are related to the environmental and clothing conditions whereas internal determinants are related to anthropometrical and physiological characteristics. The observed $T_{sk}$ is consequently the result of all these contributions (Barnes, 1963). It is important to keep in mind that thermal processes influencing $T_{sk}$ are by distinction ruled by physics; physiology is not able to modify the laws of heat transfers but can influence their quantitative importance (Houdas et al., 1975).

A specific attention must be paid to the different variations of $T_{sk}$. $T_{sk}$ variations can be temporal (over time), spatial or intra-individual or topographical (over the body) or inter-individual (over a population of individuals). It has been early recognized that $T_{sk}$ is far from uniform, even with well-clothed individuals (Benedict et al., 1919).

1.3.1. Internal determinants

1.3.1.1. Cutaneous blood flow

1.3.1.1.1. Overall mechanisms

At the skin level, cutaneous blood circulation has a nutritional role (nutrients and oxygen) and also acts to maintain thermal homeostasis by offering efficient heat transfers between the body core and the periphery (Bazett, 1958; Smith and Kampine, 1980). Blood flowing underneath the skin surface is a strong thermal exchanger by convection and represents a large avenue for heat gain at the skin. The heat exchange depends upon the blood temperature and the blood flow; the latter varies according to the skin vasomotor tone.

Vasoconstriction is triggered during body cooling from autonomic descending signals (medulla) responsible for the release of nor-epinephrine acting on the $\alpha$-receptors. This significantly reduces blood flow in the arterioles and venous plexus located in the subcutaneous regions, which in turn induces a fall in $T_{sk}$ and reduction
of dry heat loss to the environment. In the limbs, blood in the superficial veins return to the body core close to the artery (in the venous comitans) due to the constriction, hence gaining heat and limiting the drop of $T_{core}$: this phenomenon is called “counter-current heat exchange” (Bazett, 1949). A local decrease in $T_{sk}$ can produce a powerful localized vasoconstriction, independent of central afferences (Charkoudian, 2003). The reduction of heat loss by vasoconstriction is a peripheral phenomenon mainly present in the distal extremities. In non-acral regions (torso, head, proximal extremities), lowering of $T_{sk}$ during cooling may not be related to vasoconstriction but mainly due to the constant insulative properties of the skin and underlying tissues (Vangaard and Giesbrecht, 2005).

Active vasodilation is triggered in a situation of increased body heat storage (exercise or environmental heat exposure) and mediated by co-transmission from sympathetic cholinergic nerves, with an unknown co-transmitter and to a small extent nitric oxide. Human skin blood flow can increase to as much as 6 to 8 L.min$^{-1}$ or 60% of cardiac output thus reducing the distribution of blood to other organs such as the splanchnic area. A local increase in $T_{sk}$ induces a local vasodilator response predominantly dependent on local activity of the sensory nerves (Charkoudian, 2003).

In acral sites (hands, feet, lips and nose), vasodilation occurs by the alterations of the vasoconstrictor tone as these regions are solely innervated by adrenergic vasoconstrictor nerves. Moreover, these regions possess a large number of arterio-venous anastomoses (AVA) which are capillary bypasses with thick muscular walls able to shortcut the normal route of the blood from arterioles to the venous plexus (Sherman, 1963). Opening of the AVAs increases $T_{sk}$ and facilitates heat loss to the environment.

1.3.1.1.2. Cutaneous blood flow during exercise

It is well recognized that exercise induces three non-thermoregulatory effects influencing skin blood flow and consequently $T_{sk}$.

1) At the onset of dynamic exercise, there is a vasoconstriction in the finger and the forearm which is intensity dependent and more pronounced at maximal workloads (Johnson and Park, 1982).

2) Exercise also increases the $T_{core}$ threshold for cutaneous vasodilation, favouring the metabolic demand with perfusion of skeletal muscles. This is even more
pronounced with low $T_{sk}$ in cold environments responsible for a delayed onset of active vasodilation via norepinephrine release (Pergola et al., 1996).

3) Exercise induces a plateau in skin blood flow well below maximal values during prolonged duration of activity (Kenney and Johnson, 1992). After exercise, it has also been suggested that the vasodilator outflow is inhibited by a baroreceptor mediated peripheral vasoconstriction (Kenny et al., 2003).

1.3.1.1.3. Regional blood flow

General principles about blood flow regulation at rest and during exercise have been described. However, this lacks regional evaluation of the vasculature and the local variations in blood flow, decisive for the spatial variations of $T_{sk}$.

Mapping the whole-body with laser Doppler flowmetry or imaging has only been performed in two experiments (Park et al., 1997, Harbi and Thacher, 2013). They observed significant intra-individual differences in blood flow, especially with higher values in the upper body compared to the lower body or in the body core (torso-head) compared to the limbs. It is well known that the skin is fed and drained by a continuous network of arteries and veins formed by vessels whose size, shape, density and direction vary from region to region in the body (Taylor, 2007). Taylor and Palmer (2006) defined 40 vascular territories called “angiosomes” supplied by a source artery and its accompanying veins that span between the skin and the bone. Within the angiosomes, specific cutaneous perforators arise from the source artery or from one of its muscle branches allowing a transfer of blood from active muscles to the surface. These cutaneous perforators have been mapped by Taylor (2007) and are supposed to have a large role in heat dissipation. Infrared thermography has been used to study perforators (Zetterman et al., 1999; Binzoni et al., 2004; Vainer et al., 2005) and have been associated with specific thermal peaks following exercise (Hunold et al., 1992, Merla et al., 2010).
Figure 1.7 (A) Schematic representation of the cutaneous perforators and their interconnections (B) the 40 angiosomes of the human body (C) Sites of emergence of cutaneous perforators of 0.5mm diameter or greater. From Taylor (2007)

The association between $T_{sk}$ and skin blood flow has usually been reported in limited vascular regions, as demonstrated by Hunold et al. (1992) who found the circulatory heat transfer dominates the pattern of $T_{sk}$ distribution within the thigh (higher blood flow in warm areas than in cool ones). Regions with low vasculature (knuckles, patella, heavy scar) or even avascular (hair) also appear colder than adjacent vascularised areas (Barnes, 1963). However, this does not provide evidence about a consistent determinism when the whole body is considered as many other contributing factors should be taken into consideration to explain spatial $T_{sk}$ variation.

1.3.1.2. Body composition and insulation

1.3.1.2.1. Overall importance

The conduction of heat within the body depends on the core-to-skin temperature gradient and the conductivity of the different body tissues. The conductivity is inversely proportional to the resistance or insulation of the tissues which represent a barrier for heat loss from the core to the skin. The layers of muscle, subcutaneous fat and skin form the thermal body insulation.
The thickness of the skin, composed of the dermis and epidermis, is relatively small compared to its underlying tissues. The contribution of the skin layer to body insulation is marginal.

At rest, in a state of vasoconstriction, muscle accounts for up to 75% of the total body insulation (Hayward and Keatinge, 1981; Park et al., 1984; Rennie 1988). During exercise, active muscles are well perfused by blood and lose part of their insulatory capacity. However some other inactive superficial muscles may still contribute to body insulation to some extent, especially when upper-body musculature is considered during lower-body exercise.

Lipkin and Hardy (1954) has shown that fat is a poor thermal conductor and a good insulator, as compared with muscle or skin. The thermal conductivity of fat is two times lower than that of passive muscle (Anderson, 1999). Some studies have demonstrated an inverse relationship between $T_{sk}$ and percentage body fat (%BF) or mean skinfold thickness during cold resting nude exposure (Baker and Daniels, 1956; Bittel et al., 1988). It was notably found that body fat acts passively and in the same way for $T_a$ between 1°C and 10°C. As vasoconstriction was maximal in moderate cold air (10°C), this suggests that the lower level of $T_{sk}$ observed at colder ambient temperatures is due to a local passive cooling.

1.3.1.2.2. Regional contribution

On average, the skin layer is 2mm with some regional variations (1mm over the scalp, 4mm thickness over the back) having small influences on body insulation.

The contribution of the peripheral musculature depends upon the anatomical site investigated and the rate of tissue perfusion (Anderson, 1999). The muscle of the forearm can represent up to 92% of the insulation in a state of vasoconstriction (Ducharme and Tikuisis, 1991).

Similar to muscles, the relative contribution of fat thickness depends on the anatomical area, the level of thermal stress and the state of activity. It indeed represents only 8% in a vasoconstricted forearm which is a region with relatively low fat deposits (Ducharme and Tikuisis, 1991). Fat thickness distribution patterns (fat patterning) can impact regional heat loss and consequently $T_{sk}$ as firstly hypothesized by LeBlanc (1954). He suggested that the variations of fat thickness over the body explain to a certain extent the regional variations of $T_{sk}$. This assumption has never
been confirmed quantitatively despite the general agreement that skin over fat deposits tends to cool more than adjacent skin during cold exposure (Frim et al., 1990).

Most studies looking at the association between $T_{sk}$ and fat have focused on the inter-individual variability at specific body regions (Livingstone et al., 1987; Frim et al., 1990). Frim et al. (1990) still provided some insights in the intra-individual variability suggesting that the shape and size, rather than the thickness of the fat pads, are the most important factors associated to $T_{sk}$ variations.

Edwards (1950) performed the most extensive skinfold thickness evaluation to date with the measurements of 53 body sites, finding a large heterogeneity in fat distribution especially on the torso. Mueller (1985) indicated that individual differences in fat patterning exist between upper vs lower limb or upper vs lower trunk, with the main distinction highlighted by the gynoid vs android continuum (Vague and Fenasse, 1965). The android pattern corresponds to a fat distribution mainly around the upper body in areas such as the abdomen, chest, shoulder and this is most commonly found in males. On the other hand, the gynoid pattern corresponds to a fat distribution around the hip and buttocks, most commonly found in females.

1.3.1.3. Body anthropometry and heat production

1.3.1.3.1. Overall importance

Heat exchange with the environment depends upon both the thermal gradient between the skin and the environment and the surface area across which heat exchange may occur. Heat production and storage depend upon both the total mass of the body and its relative composition (Anderson, 1999). A large surface area, favourable for evaporative and dry heat exchange, is yet often accompanied by greater mass associated with larger heat production and increased insulation (Anderson, 1999).

Surface area for the whole-body is generally determined from body mass and height using the equation of DuBois and DuBois (1916). Body mass determines metabolic load and heat storage capacity, with the specific body heat of lean tissues two times larger than fat tissues.

The surface area-to-mass ratio ($A_{Du}/M$) combines the heat loss and heat production capabilities of the body. An average adult has a $A_{Du}/m$ about half of a newborn baby.
and it is suggested that young children require 5 times the heat production per unit of mass of an adult to maintain thermal equilibrium (Hensel, 1981). The role of $A_{Du}/M$ may not be that significant for thermoregulation during cold exposure (Anderson, 1995) and during exercise a more relevant factor could instead be the heat storage capacity (Havenith, 2001a).

Heat production increases with exercise but also through autonomic shivering, around five times the non-shivering levels (up to 300 W.m$^{-2}$).

Non-shivering thermogenesis has regained interest with the discovery of brown adipose tissue (BAT) in adult humans, especially in lean individuals exposed to cold (van Marken Lichtenbelt et al., 2009). The thermal significance of active BAT remains to be elucidated but the dense network of blood vessels perfusing these cold-activated tissues may also represent an alternative reason for local warmer spots at the skin surface compared to the surrounding tissues (Symonds et al., 2012).

Skin heat production is relatively constant and usually considered as negligible around 6.5 W.m$^{-2}$ (Houdas et al., 1975).

1.3.1.3.2. Regional contribution

The regional heat loss and heat production capabilities can also modify regional $T_{sk}$ bearing in mind the dynamic interplay with all the other determinants.

At a segmental level, it is clear that differences exist between the trunk (small surface area-to-mass) and arms (large surface area-to-mass) and can affect $T_{sk}$ in conjunction with the small thermogenic capacity but large changes in vasomotor tone of the arms. The thermogenic influence of active lower leg muscle has been clearly highlighted by thermographic investigations (Clark et al., 1977; Vegthe et al., 1979). Cooper et al. (1959) suggested a direct radial vascular convection of heat from active muscle to overlying skin via venous blood flow. The low proportion of fat of the calves may also contribute to the increase in regional $T_{sk}$.

Mapping of muscle activity (indirectly local heat production) has become available with the use of positron emission tomography (PET) and the uptake of $^{18}$F-fluorodeoxy-glucose (FDG) in body tissues (Fujimoto et al., 1996). This has many advantages over multiple electromyogram recordings proposed by Werner and Reents (1980). Regional heat production during shivering is mainly triggered in the proximal muscles of the upper limbs and then the trunk and thigh muscles (Bell et al., 1992).
The morphology and geometry of the human body also creates regional specificities modifying the heat transfers between skin surfaces. A cross radiation effect (surface facing each other) may be seen in all body cavities or creases where skin opposes skin e.g the navel, the inner canthus of the eye, the inner thighs, the interior of the ear, the lip line, and the area between fingers if they are held close together (Barnes, 1963).

1.3.1.4. Evaporation of sweat

1.3.1.4.1. Overall importance

Evaporation of sweat relies on sweat production (internal) and the evaporative cooling power of the environment (external). The latter can be determined by the water vapour pressure of the environment and depends on a combination of $T_a$ and relative humidity, defined by psychometric charts.

For a given evaporative cooling power of the environment and all other parameters kept equal, $T_{sk}$ will be lower the larger the sweat production. Heat loss is 675W for one litre of sweat evaporated within an hour. Evaporative heat loss has been positively correlated with $T_a$ (at low relative humidities) and it was also higher the larger the metabolic rate (Davies et al., 1976). In humans, sweat rate for the whole-body can reach 1L.h$^{-1}$ during exercise and even 2.7 L.h$^{-1}$ during exercise in the heat. The relative contribution of thermal signals for sweating is approximately from 6:1 to 20:1 for $T_{core}$ and $T_{sk}$ respectively (Nadel et al., 1970; Wyss et al., 1974). Eccrine sweat glands are stimulated by cholinergic sympathetic nerves and secrete sweat non-uniformly onto the surface of the skin.

1.3.1.4.2. Regional contribution

Evaporative heat loss varies in different body regions for nude resting males, higher values found at the forehead and hands with all values increasing sharply above 30°C air temperature (Werner and Reents, 1980). The regional sweat production during exercise (not the evaporation) has been extensively quantified in recent years with either ventilated capsules or absorbent pads (Havenith et al., 2008a; Machado-Moreira et al., 2008; Smith and Havenith, 2011, 2012). A clear distinction was observed between regions of high sweat rates (central and lower posterior torso) and lower sweat rates (towards the extremities). Regional sweat rates were not correlated
with regional \( T_{sk} \) whilst exercising in a 25°C environment (Havenith et al., 2008a). It is worth noting that vasodilation is further stimulated by sweating and provides the blood supply that carries fluid to the sweat glands. The presence of warm blood close to the body surface consequently raises \( T_{sk} \) or dampens its decline.

In summary, the internal determinants affect \( T_{sk} \) either passively (body composition and anthropometry) or actively (vasomotor tone and evaporation). The relative importance of the active physiological mechanisms is great insofar as it also modifies the role of the passive components within the body. The regional variations of internal determinants contribute to a great extent to the spatial \( T_{sk} \) variations.

### 1.3.2. External determinants

External determinants of \( T_{sk} \) combine environmental determinants (\( T_a, rh, \nu, T_r \)) and the type of clothing ensemble worn by the individual. In some everyday life situations, especially outdoors, the characteristics of the environment are relatively uncontrollable in contrast with the decision to wear clothing.

#### 1.3.2.1. Air temperature

The influence of \( T_a \) is of primary importance for \( T_{sk} \). \( T_a \) contributes to the convective heat transfer and also to radiative heat transfer when no specific external radiation sources are present. An almost linear relationship between \( \bar{T}_{sk} \) and \( T_a \) has been found over a range from 5°C to 30°C at rest and during exercise where sweating is limited (Gagge et al., 1938; Werner and Reents, 1980). This was also observed for regional \( T_{sk} \). The pattern of regional \( T_{sk} \) measured by contact sensors was only little affected by air temperature (Werner and Reents 1980). This was confirmed by infrared thermography investigations showing similar features at different environmental temperatures (Clark and Edholm, 1985).

On the other hand, the range of \( T_{sk} \) was greatly influenced by \( T_a \), with a maximal difference between body regions as large as 17°C in the cold environment (Werner and Reents, 1980). This range of \( T_{sk} \) becomes more homogenous with increasing \( T_a \). \( T_{sk} \) depends on \( T_a \) and is little affected by metabolic rate whereas it is the opposite for \( T_{core} \) (Hardy et al., 1971). In general, \( T_{sk} \) also responds more directly to abrupt changes of thermal load than of work load, in contrast with \( T_{core} \) (Werner et al., 1985).
1.3.2.2. Relative humidity

The interaction between $T_a$ and relative humidity ($rh$) determines the evaporative cooling power and therefore the efficiency of sweating. In cold environments, the water vapour pressure of the air is relatively low even at high $rh$, thus favouring sweat evaporation at the skin surface (Pugh, 1970; Adams, 1977). Above 18°C $T_a$, Winslow (1937) demonstrated that $T_{sk}$ was similar at both high (>$60\%$) and low $rh$ (<30%). The body responds to high vapour pressure by an increased blood supply to the skin (higher skin conductance) and an increased secretion of sweat (higher wetness) to maintain evaporative heat loss at the desirable level. Higher $T_{sk}$ can yet be expected for exercise in a given warm or hot air temperature (minimized convective heat loss or even heat gain) when $rh$ is high (>85%) compared to low $rh$ where $T_{sk}$ would be reduced via greater evaporation of sweat produced.

Water condensed from the atmospheric vapour becomes rain when precipitating in the form of droplets. This will directly impact the exposed skin by large conductive heat loss and clothing insulation by an increased dry heat loss. Thompson and Hayward (1996) demonstrated that rain (7.4cm.h$^{-1}$) in a 5°C $T_a$ induced a 5°C drop in $T_{sk}$ compared to a no-rain condition.

1.3.2.3. Air flow

Airflow around the body caused by the air velocity and / or the body motion determines the convective heat transfer in conjunction with $T_a$. For a resting man, Iampietro (1961) observed that wind speed modified the sensitivity of the $T_{sk}$-$T_a$ relationship over the -4°C to 35°C range. In cold environments, the influence of air velocity on resting regional $T_{sk}$ was quantified on the face (nose, forehead, cheek) by LeBlanc et al. (1976) and several body regions under clothing by Mäkinen et al. (2000). During running, the coefficient around the thigh can be twice as large as in a still position ($h_c = 54$ W.m$^{-2}$.K$^{-1}$) due to the swinging “pendulum” motion. The extra heat loss due to the wind appears to be additive with the heat loss from the swinging leg in the absence of wind (Clark et al., 1974).

Increase in air velocity also modifies the evaporative heat transfer coefficient ($h_e$) and can be effective for heat dissipation in most conditions (Adams, 1977). The airflow can be created by exercising movement (even during stationary cycling) and
provides substantial convective and evaporative heat dissipation. Davies (1980) observed that slowing down the running pace (from 15 km.h\(^{-1}\) to 11 km.h\(^{-1}\)) with the same air velocity induced an increase in \(T_{sk}\) and local sweat rate. This demonstrates the importance of the body motion relative to the wind on convective and evaporative heat loss. Several studies have quantified the impact of forced convection on \(\bar{T}_{sk}\) during exercising protocols but regional \(T_{sk}\) values have rarely been reported (Haymes et al., 1982; Adams et al., 1992; Tsuzuki et al., 1993).

Thermographic measurements of a runner in the presence of wind and in still air revealed that \(T_{sk}\) changes were larger and more rapid with airflow. The patterns of increased temperature due to active muscle were still dominant (Clark and Edholm, 1985). These authors also emphasized that the body is rarely subjected to truly linear forced convective flow, the outdoor wind being invariably turbulent and multidirectional. Davies (1980) found identical \(\bar{T}_{sk}\), \(T_{core}\) and overall sweat rate (running at 70% \(\dot{VO}_2\max\) at 21°C \(T_a\)) irrespective of the wind direction.

### 1.3.2.4. Radiant temperature

As indicated by Nielsen et al. (1988), most studies on human thermoregulation have been performed in climatic chambers as opposed to the natural outdoor environment, where physical activity is most often practised. They quantified the influence of solar radiation on semi-nude and clothed participants exercising on a cycle ergometer (Nielsen et al., 1988, 1990). Approximately 100W of direct short-wave radiation was absorbed by the semi-nude body with either the back or the front exposed to the sun. At 25°C air temperature with an addition of 700 W.m\(^{-2}\), they also found that \(\bar{T}_{sk}\) and overall sweat rate were elevated in black compared to white clothing of similar material.

With different protocols (indoor with solar panels, outdoor with clear-sky solar radiation), other studies using exercise have demonstrated a rise of approximately 1 to 2°C in \(\bar{T}_{sk}\) with additional radiation compared to cloudy skies or no radiation indoor (Adams et al., 1977, Tsuzuki et al., 1993). Using thermography, Clark and Edholm (1985) observed a 5-6°C \(T_{sk}\) increase in body regions exposed to sunlight compared to shaded regions.
A controlled study on the intensity and type of solar radiation revealed a curvilinear positive relationship between $T_{sk}$ of resting individuals and the radiation intensity between 0 and 600 W.m$^{-2}$ irrespective of the spectral content of the stimulated radiation (Hodder and Parsons, 2002). There was a 3°C difference in $T_{sk}$ between no solar load and 600W.m$^{-2}$ after 30 minutes of exposure, leading to an increase of thermal sensation by 3 scale units on the ASHRAE scale (11 points). Chest $T_{sk}$ was the highest at all intensity conditions.

1.3.2.5. Clothing

Clothing can be considered as an additional behavioural effector response, adjusted to the climate to allow other effector responses (physiological) to stay within their utility range (Havenith, 2003). Clothing was decisive for the expansion of humanity in regions on earth below 20°C where our thermoregulation mechanisms would not be sufficient to maintain body functions in the long term. Clothing acts as a resistance to heat and moisture transfer between the skin and the environment. In this way it can protect against extreme cold, but at the same time it hampers the loss of superfluous heat during physical effort (Havenith, 2003).

1.3.2.5.1. Clothing main characteristics

A garment can be classified according to its insulation or heat resistance and vapour or evaporative resistance. The insulation of a clothing ensemble is mainly determined by the amount of air trapped inside and on the surface of the textiles (Larose, 1947). Insulation and vapour resistance are much more influenced by these characteristics than by the fibre type (natural vs synthetic), yarn type (staple vs filament), fabric construction (woven vs knit).

Clothing insulation represents a barrier to convective and radiative heat loss. It is expressed in m$^2$.K.W$^{-1}$. An insulation equivalent was invented by Gagge et al., (1941), the Clo unit defined by the amount insulation necessary to maintain resting comfort and $T_{sk}$ at 33°C at 21°C $T_a$ (1 Clo = 0.155 m$^2$.K.W$^{-1}$). Several factors are involved in the determination of clothing insulation such as physical activity, air velocity, posture or clothing fit (Nielsen et al., 1985, Havenith et al., 1990a). Movement and posture mainly influence the intrinsic clothing insulation whereas wind mainly affects the surface air insulation. Tight clothing fit shows a 6-31%
lower insulation than loose fit (Havenith et al., 1990a). Moreover, the insulating value of clothing can be reduced considerably when air in the textile cavities is replaced by sweat (Hall and Poltke, 1956). Conductive heat loss will be profoundly increased in wet clothing. The evaporation of sweat after the cessation of exercise in the cold can cause the so called “post-exercise chill” associated with an uncomfortable contact with wet fabric on the skin (Bakkevig and Nielsen, 1994).

Garment vapour resistance impedes the diffusion of water vapour through the garment and modifies the capacity for evaporative heat loss. It is expressed in m².kPa.W⁻¹. Some fabric finishes, membranes or coatings can largely increase vapour resistance with the extreme limit of impermeable materials, potentially blocking the diffusion of vapour molecules. On the other hand, the reduction of evaporative resistance can be very important due to the combination of wind and movement (Havenith et al., 1999).

As indicated by Nielsen and Endrusick (1992), all these factors influencing heat and vapour resistances will vary from site to site. Local areas on the human body are not thermoregulatory independent, thermal processes at one location in the clothing may interact with processes in the neighbouring areas.

1.3.2.5.2. Clothing and skin temperature

Clothing insulation and vapour resistance, in interaction with many external factors, will define the microclimate between the skin and the innermost layer of clothing, which will in turn affect $T_{sk}$. Nielsen et al. (1989) highlighted a 0.3°C warmer $T_{sk}$ for a tight-fitting layer versus a loose-fitting layer in cold and neutral environment. On the other hand, a clothing ensemble of similar insulation (1.6 Clo) but different knit structure exhibited regional $T_{sk}$ differences up to 3°C (fleece warmer than fishnet) during intermittent exercise in the cold (Nielsen and Endrusick, 1990). During exercise in the cold, Nielsen and Endrusick (1992) demonstrated that temperatures of the clothing layers generally changed more than the corresponding $T_{sk}$.

As can be expected, some authors found the local $T_{sk}$ to be dependent on the local clothing insulation. $T_{sk}$ was always higher in more insulated locations at rest and during exercise (Gwosdow and Berglund, 1987; Nielsen and Nielsen, 1984; Rissanen et al., 1996). The previous studies manipulated clothing insulation distribution by adding insulation on different body parts (Nielsen and Nielsen, 1984) or by having asymmetrical distributions (Gwosdow and Berglund, 1987; Rissanen et al. 1996).
Nielsen and Nielsen (1984) stressed that insufficient clothing insulation may cause cold-induced vasoconstriction and a change in $T_{sk}$ and its distribution. The character of this change will depend on the placement of the insulation of the clothing over the body surface (Nielsen and Nielsen, 1984). This comment highlights the significance of a regional distribution of clothing insulation. Changing the insulation over specific regions of the body with different thermal needs may improve the local and/or overall thermal comfort of the wearer. Recently, Havenith et al. (2008b) suggested that the insulation should be placed over cold regions of the body in order to improve comfort whereas the warm regions with a high heat loss should be targeted if personal protection against hypothermia is most relevant. This was also suggested by Hertzmann (1959) with the observation that head and trunk should be the better insulated to reduce heat loss. In -15°C conditions, Brajkovic (1998) observed that an addition of heating in the trunk was sufficient to maintain hand comfort and dexterity. Further explorations are needed to demonstrate the potential benefits of local clothing insulation only with no additional elements or gear.

In summary, external determinants influence $T_{sk}$ with $T_a$ being one of the most important predictor of $T_{sk}$. Humans adapt to a large variety of $T_a$ by behavioural adjustments such as changing to a more adequate climate and a good way to control its own micro-climate is to modify the clothing worn. $T_{sk}$ will be dependent on the thermal properties of the clothing ensemble affecting the heat transfers between the skin and the environment. Though environmental parameters mainly influence the absolute values of $T_{sk}$, clothing can have a regional impact depending on the regional distribution of heat and vapour resistance.

### 1.3.3. Additional specificities

The combination of internal and external determinants is decisive to understand the variations in $T_{sk}$ in different contexts and also to understand the regional topography of $T_{sk}$ within an individual. Environmental determinants influence the absolute values of $T_{sk}$ for all individuals whereas internal determinants may vary from site to site, therefore influencing $T_{sk}$ spatial variations within an individual.

There is a large inter-individual variability in internal parameters. The following personal characteristics can therefore modify the internal determinants and lead to
different thermal responses, potentially explaining discrepancies in $T_{sk}$ and specific regional variations.

1.3.3.1. Age

The $T_{sk}$ distribution over infants nursed in an incubator was shown to be reminiscent of that found over adults in moderate and warm environments (Clark et al., 1980) with the “hot core” and temperatures diminishing towards the extremities, the cephalo-caudal distribution of $T_{sk}$ (Candas, 2005). Thermographic evaluation of infants also highlighted the warmest areas at the nape and interscapular regions which correspond to the location of BAT, releasing heat from oxidation of free fatty acids (Rylander, 1972). The $T_{sk}$ distribution for a population of 25 children has been thermographically obtained showing the highest $T_{sk}$ at the forehead, neck and cervical areas with no distribution difference between boys and girls (Kolosovas-Machuca and Gonzalez, 2011).

From birth to maturity, height, weight and surface area increases 3.5, 19 and 9 times respectively and the ratio of surface area-to-mass drops substantially from birth to adolescence (Little and Hochner 1973, in Anderson, 1999). The larger surface area-to-mass ratio of children may be a disadvantage for heat dissipation in the cold but it has been found that pre-pubertal children react more rapidly to cold than older children or adults, defending their $T_{core}$ with different effector response patterns (Anderson 1999). During cold exposure, pre-pubertal boys (10 years) maintained similar $T_{sk}$ in chest, back and forehead than young men (22 years) but they had lower $T_{sk}$ in the finger and thigh (Inoue et al., 2006). During exercise in the cold, children are characterized by lower $T_{sk}$ (Falk, 1994).

In general, the effect of ageing has been associated with an attenuated vasoconstrictor response during cold exposure irrespective of fitness level and body anthropometry (Falk et al., 1994) as well as a reduced vasodilation during heat stress (Kenney & Havenith 1993).

Age is negatively correlated with skin and subcutaneous fat thickness (Petrosfsky et al., 2008), and sarcopenia (the reduction of muscle mass with age) may also reduce tissue insulation and the thermogenesis capacity (DeGroot et al., 2006, Kenney and Munce, 2003).
1.3.3.2. Sex

Cautious considerations must be taken when exploring the differences in thermoregulatory responses between males and females. Most studies have not matched males and females for anthropometry (body composition and morphology) or physical fitness level at the same time. It is also very difficult to vary surface area without mass and adiposity (Havenith, 2001a). The sex differences obtained are often the resultant of a combined effect of internal determinants and physical fitness that differ between males and females. Most women have greater fat content and thicker subcutaneous fat thickness than men of comparable weight and age (Sawka and Young, 2000). During resting cold exposure, the advantage of higher fat content can be offset by the slightly larger $A_{Du}/m$ in females. During exercise, the heat storage will be more important for a large proportion of fat in body composition (specific heat of fat two times smaller than lean body tissue) but this could be offset by the generally smaller mass of females (Cheung et al., 2000).

$T_{sk}$ is usually 1 to 2°C colder for the “average” representative females compared to representative males at rest and during exercise in the cold (Graham, 1988). This discrepancy has sometimes been attributed to body fat (Wyndham, 1964) but others have not been able to show a relationship (Stevens et al., 1987). During resting cold exposure, a greater peripheral vasoconstriction has been observed in females by some authors (Burse, 1979) but not others (Wagner and Horvath, 1985). In a thermoneutral environment, Park et al. (1997) found no gender differences in cutaneous blood flow mapped for 60 men and 60 women over 14 sites on the anterior body. Gender differences were not found in peripheral $T_{sk}$ (finger, nose or chin) during exercise in cold air (Stevens et al., 1987; Graham, 1983). Thermographic comparisons of males and females have only been performed for one individual in a thermoneutral environment (Clark and Edholm 1985).

As previously mentioned, most of the variations between males and females could be accounted for by matching the participants for morphology and fitness level (Havenith, 2001a). However, main sexual dimorphism exists in terms of hormonal secretions (Gatford et al., 1998) and lipid metabolism (Mittendorfer, 2005). Cyclic secretion of hormones (progesterone, oestrogen) leads to the menstrual cycle in females. The thermogenic and central effect of progesterone may explain the higher $T_{core}$ (0.5°C) during the luteal phase of the menstrual cycle compared to the follicular
phase. This has been associated with a higher threshold for the onset of sweating (Stephenson and Kolka, 1985).

Differences in lipid metabolism can explain differences in body composition and the gender specific distribution of subcutaneous fat. Fat patterning indeed differs between males and females. In men, increases in fat tend to accumulate in the abdominal region and upper parts of the body whereas in women it is located in the lower body, particularly in the gluteal and femoral region (Tur, 1997). Fat patterning potentially modifies regional heat loss and in turn $T_{sk}$ but an extensive regional thermographic evaluation of males and females has never been performed.

1.3.3.3. Geographic origins, ethnicity, cold adaptation, cold acclimatization

Climatic conditions change radically between different regions of the world and seasonal variations also occur during the year. The variety of climates has conditioned the evolution of humans through genotypic and phenotypic adaptations (Taylor, 2006).

*Phenotypic thermal adaptation* occurs when an organism modifies either its morphological configuration (e.g subcutaneous adipose tissue thickness, sweat gland size) or its physiological responses, following repeated stress exposure. There is no conclusive evidence of specific ethnic differences in cold adaptation (Taylor, 2006). Greater peripheral vasoconstriction, thus reduced $T_{sk}$, has yet been observed in Australian Aborigines compared to Caucasians, and this physiological response remained even years after adopting European dress and lifestyle (Scholander et al., 1958). Adaptation to cold climate can be classified into three types: the *insulative* adaptation to reduce heat loss by enhanced insulation (vasoconstriction); *hypothermic* adaptation allowing $T_{core}$ to fall to reduce heat loss; *metabolic* adaptation through increased heat production (Rivolier et al., 1988). Reduced $T_{sk}$ due to insulative adaptation was also found in Ama divers, nomadic Lapps or Caucasians during acclimation (phenotypic changes) or acclimatization (induced by prolonged exposure) or by cold-water immersion (Launay and Savourely, 2009).

*Acclimatization* to cold environments does not improve the cold-induced vasodilation (CIVD) response (Cheung and Daanen, 2012). The commonly larger CIVD response in humans residing or working in cold environments may potentially be due to genetic pre-disposition or self-selection for specific occupations (e.g fishermen).
Moreover, *seasonal acclimatization* has been associated with no change in $T_{\text{core}}$ nor $T_{sk}$ temperatures but an increase in the shivering response towards the summer and increased total heat production in winter (van Ooijen et al., 2004).

In general, it is well recognized that humans possess less capacity for cold adaptation than heat adaptation (improved sweat response and circulatory stability) with behavioural adjustments being largely responsible for the survival in cold to extreme cold environments, such as the Lapps or Eskimos maintaining $T_{sk}$ between 31 and 34°C under their clothes at -10°C (Scholander et al., 1957).

For the assessment of $T_{sk}$, it is worth mentioning that skin emissivity remains the same ($\varepsilon = 0.98$) regardless of the ethnic background and geographic regions of origin although skin pigmentation varies widely between different regions of the world (Barnes, 1963). Skin pigmentation indeed plays no role in the longer-wavelength region, where the skin is an almost perfect absorber and accordingly a near perfect emitter as opposed to the lower part of the spectrum (near infrared $< 2\mu m$ and visible).

### 1.3.3.4. Circadian rhythm

The daily variations of body temperatures occur in a cyclical fashion (with a period of 24-25h), they are known as *circadian rhythms*. The variations are of approximately 1°C in magnitude for $T_{\text{core}}$ and can be explained by a circadian change in the temperature set-point. The circadian rhythmicity results from interactions between clock genes and clock proteins, in close association with the sleep-wakefulness cycle (Clayton et al., 2001 in Reilly and Waterhouse, 2005). $T_{\text{core}}$ follows a cycle similar to a cosine function with a peak (acrophase) in the afternoon (around 5pm) and lowest value (mesor) around mid-sleep (4am) (Reilly and Waterhouse, 2009). Aschoff and Heise (1972) showed that this cycle was out of phase with heat loss from the extremities. $T_{sk}$ in the hands is increasing at night whilst $T_{\text{core}}$ is decreasing. The changes in heat loss from the extremities may account for 75% of the circadian variation in $T_{\text{core}}$. On the other hand, daily variations in chest and upper arm $T_{sk}$ were relatively minimal. Van Someren (2000) reviewed the link between circadian temperature variation and sleep highlighting the association between warm $T_{sk}$ and cerebral activations for sleep. Thermographic evaluations throughout a day (in a 22°C environment) revealed that the patterns of $T_{sk}$ distribution remained consistent with only few localised differences (e.g 1°C higher
$T_{sk}$ over the abdomen at 6pm than 8am) (Bianchi et al., 1976). Several studies reported no significant differences in $T_{sk}$ temperature between a morning and evening exercise (Reilly and Garrett 1995, Torii et al., 1995).

1.3.3.5. Fitness level

Fitness level corresponds to one of the most important factors involved in inter-individual differences in thermoregulation. Fitness level is quantified in terms of the maximal aerobic power ($\dot{VO}_{2,max}$) and the rise in $T_{core}$ has been associated with the relative value of this maximal aerobic power (Saltin and Hermansen, 1966; Nielsen, 1969) though a bigger importance of the absolute value has recently been suggested (Jay et al., 2011). There is no consensus about the effect of fitness on thermal responses to cold. Some authors found higher $T_{sk}$ and heat production for men with higher $\dot{VO}_{2,max}$ (Bittel et al., 1988) but no significant differences for others (Budd et al., 1991). In both cases, the effect of fatness had been removed by partial correlation techniques. The effect of physical conditioning is also inconclusive with even opposite results for $T_{sk}$ (Adams and Heberling, 1958; Kollias et al., 1972). Kollias et al., (1972) suggested that the major factor in human tolerance to cold appears to be the relative proportion of body fatness particularly subcutaneous fatness irrespective of the state of physical condition.

In summary, the influence of additional personal factors is difficult to interpret considering the combined influence of many determinants. The isolation of a specific factor is sometimes not possible and a large majority of the knowledge is confined to representative individuals of a population. Moreover, the main mechanisms of human thermoregulation are commonly reported with overall classical indices ($T_{core}$ and $T_{sk}$) and no consideration for regional values. Regional specificites may not be of thermoregulatory significance (autonomic) but may have significant perceptual consequences for human behaviours, which is rarely evaluated.
SUMMARY

$T_{sk}$ variations can be extremely large in different life situations and across the body of the same individual. Unlike $T_{core}$, the maintenance of a narrow range of $T_{sk}$ during the day is not critical for human survival despite the risk of skin injuries at some $T_{sk}$ extremes below 5°C and over 45°C (frostbite, burns). $T_{sk}$ is nevertheless highly important for human thermoregulation and reflects the dynamic interplay of several internal and external determinants.

- $T_{sk}$ is resultant of **heat transfers** through four physical pathways (conduction, convection, radiation and evaporation) occurring within the body and from the skin to the environment.
- Every **passive factor** or **active mechanism** of the body or the environment can change the magnitude of the four heat transfers, and consequently modify the resulting $T_{sk}$. This can occur at a whole-body level or at a regional level.
- There are important limitations to use **contact sensors** in order to map $T_{sk}$ over large surface of the body. The $T_{sk}$ range can be extremely large both for the whole-body and within a body region. The best available method for the measurements of the spatial variations of $T_{sk}$ in a nude body is **infrared thermography**. The $T_{sk}$ topography can then give valuable information about the overall and regional $T_{sk}$ with great spatial sensitivity.
- **Cutaneous thermoreceptors** in the skin respond to static $T_{sk}$ or dynamic change of $T_{sk}$ and transmit the signal to the hypothalamus where the integration leads to the initiation of autonomic thermoregulatory adjustments.
- **Internal $T_{sk}$ determinants** are mainly affected by these changes in the autonomic thermoeffector responses, with adjustments of the vasomotor tone (vasoconstriction or vasodilation) and sweating. Body composition (skin, fat, muscle) and body anthropometry passively contributes to the potential for heat loss within the body in conjunction with the physiological adjustments that can be modified by exercise. Individual characteristics such as age, sex, acclimatization and fitness level also influence the active or passive internal determinants. Internal determinants may be the key reasons for the spatial $T_{sk}$ variations across the body and also inter-individual variations.
- **External $T_{sk}$ determinants** define the thermal stress endured by the skin with a strong contribution of $T_a$, airflow and vapour pressure, and to a lesser extent external radiation. Clothing represents another important external determinant that will affect uniformly the quantitative value for $T_{sk}$ in most cases. External determinants play a large role in the temporal $T_{sk}$ variations.

- The signalling role of $T_{sk}$ has been demonstrated for both the **autonomic and behavioural regulation** in conjunction with thermal signals from deep and central thermoreceptors. Thermal perceptions (sensation and comfort) are triggered after integration of the signal in the cortex and lead to the thermal behaviour.

- **Clothing** represents one form of behavioural regulation developed by humans to overcome the challenges of the environment, additionally to autonomic thermoregulation, especially the cold conditions.

- Modifications of the clothing ensemble have rarely been reported in the literature. Notably, changes in clothing insulation can influence regional $T_{sk}$ and potentially discomfort experienced by an individual.

- **Figure 1.8** represents a schematic summary of the different heat transfers involved in the determination of $T_{sk}$ and the various internal and external determinants modifying these heat transfers.
Figure 1.8 Schematic representation of the internal and external determinants of skin temperature, affecting the heat transfers by conduction (K), convection (C), radiation (R) and evaporation (E). External determinants are air temperature ($T_a$), radiant temperature ($T_r$), air velocity ($v$) and relative humidity ($rh$).
RESEARCH DIRECTONS

The present work will mainly provide a large descriptive overview of $T_{sk}$ topography for various situations or individuals with a strong emphasis on exercise in cool to cold environments (5 to 20°C $T_a$). A specific method of image processing will be designed and implemented in the various investigations for that purpose. The extensive descriptive procedure decided in close partnership with the funding body will be a good opportunity to explore the relative contribution of the different external and internal determinants. The local and overall physiological data will always be associated and analysed with perceptual responses (thermal comfort and sensation).

The first part of the thesis will focus on $T_{sk}$ mapping of nude participants to highlight the topography without the interference of clothing.

- **Chapter 3 and 4** will deal with the inter-individual variations in body composition, especially body fat content and subcutaneous fat thickness (internal)
- **Chapter 5** will address the role of local heat production (internal) and the influence of $T_a$ (external) on $T_{sk}$ and its distribution.

The second part of the thesis will focus on $T_{sk}$ mapping of clothed participants to highlight the specific influence of clothing on $T_{sk}$ and its distribution.

- **Chapter 6** will describe the natural variations of $T_{sk}$ during a simulated real life scenario where internal and external determinants were varied.
- **Chapter 7** will aim to manipulate $T_{sk}$ according to existing $T_{sk}$ topography in order to explore its effect on thermal perceptions.

The first goal of the thesis will be to bridge the gap in the literature about the spatial variations of $T_{sk}$ with an original technique.

Secondly, the fundamental knowledge developed will be useful to understand a large variety of responses between individuals and between conditions.
Lastly, the manipulation of $T_{sk}$ distribution will help to define the benefits or disadvantages of non-uniform clothing insulation distribution in the quest for thermal comfort during exercise.

The present work will not address the influence of wind direction/turbulence, vapour pressure, external radiation, ethnicity, ageing or circadian rhythm on $T_{sk}$ and associated perceptual responses.
CHAPTER 2
Experimental methodology

Chapter Summary

This chapter describes the experimental research methods used to investigate whole-body $T_{sk}$ and associated parameters in the present series of studies. The main goal is to provide descriptive information on $T_{sk}$ and its variation over the body surface via a bodymapping approach using infrared thermography. The generic procedure for infrared measurements and data processing are presented in detail. Methods and procedures specific to single experiments are described where appropriate in the relevant chapters.

2.1. Introduction

In the field of thermal physiology, only limited research has focused on $T_{sk}$ mapping. As previously highlighted (Chapter 1.1), $T_{sk}$ measurements are mainly performed to obtain an estimation of $T_{sk}$ via contact methods. The reliability of such contact measurement to infer $T_{sk}$ over a body region is questionable considering the potential point-to-point $T_{sk}$ variation (Frim et al., 1990). However, covering the whole body surface area with numerous sensors is not a realistic approach. $T_{sk}$ body-mapping therefore requires a non-contact method with high spatial resolution. Infrared thermography provides the adequate tool for this purpose allowing large areas to be sampled at the same time. Continuous monitoring is however difficult due to misalignment of regions of interest caused by body motion (even at rest) and excessive processing time. Multiple measurements are therefore required to explore the temporal $T_{sk}$ variations. The aim of the research was firstly to fully develop a standardised procedure for whole-body $T_{sk}$ mapping, and secondly to investigate the various determinants involved in the variations of $T_{sk}$ over the whole-body in resting and exercising conditions in the cold. Relationships could then be established
between regional physiological or perceptual responses and the standardised information on regional $T_{sk}$ obtained via the $T_{sk}$ mapping approach.

2.2. Experimental design

$T_{sk}$ mapping was obtained over the whole-body at specific time points during the different studies. Separate thermograms were taken for the main regions of the body in order to obtain whole-body coverage with adequate resolution. From data collection to data analysis of the thermograms, a similar generic procedure was used allowing for comparisons between different stages of the same protocol or between studies.

2.2.1. Ethical clearance and safety

The laboratory methods for all experiments undertaken are described under generic experimental protocols (G03-P13: thermoregulatory effects of cooling in air, G03-P14 thermoregulatory effects of warming in air), which were approved by Loughborough University’s ethical committee.

2.2.2. Informed consent and health screen questionnaire

All participants were provided with a participant information sheet informing them of the aims and procedure of the experiments. They were permitted to familiarise themselves with the laboratory and the equipment before signing an “informed consent” document (Appendix A). A generic “health screen questionnaire” (Appendix A) was completed by every participant to ensure they were suitable to take part in the study.

2.2.3. Safety and withdrawal criteria

The various experiments performed throughout the course of this research exposed the participants to cold environments with exercise workloads sufficient to avoid any cold stress though always limited to rule out the risk of heat stress. The following safety rules were also adopted:

- Participants were reminded that they could withdraw from the experiment at any time, without providing a reason.
• Participants were frequently asked about their physical condition and were required to respond verbally
• Participants were not permitted to leave the laboratory after the experiment until their heart rate (HR) and core temperature \(T_{\text{core}}\) had returned sufficiently close to resting level and they felt well enough to do so.

Strict withdrawal criteria were adhered to. Experimental protocols would have been terminated in any of the following instances:

1. At the request of the participant
2. At the discretion of the experimenter
3. At completion of pre-decided duration for exposure
4. If the participant’s \(T_{\text{core}}\) rose by 2°C or increased to an absolute value of 39°C during heat exposure
5. If the participant’s \(T_{\text{core}}\) falls by 1.5°C or dropped to an absolute value of 35°C
6. If regional \(T_{\text{sk}}\) fell below 5°C (skin temperatures below 5°C have been shown, in prolonged exposures, to leave the subject at risk of non-freezing cold injury)
7. If participant HR rose above 85% of the age related predicted maximum for that participant (85% of \([220-\text{age}]\) beats per minute) when dealing with healthy, untrained participants.

### 2.2.4. Participant Recruitment

Participants were recruited from the student and staff population at Loughborough University via email and poster advertisements. Suitability was determined via a series of inclusion criteria specific to each study (described in each chapter). All participants were required to have no current injuries or medical conditions preventing them from exercising continuously for 60 minutes.

### 2.2.5. Pilot studies

Preliminary work was carried out to determine the optimal settings for infrared measurements. Thermal camera and body positions were defined so that all individuals could be recorded regardless of their body dimensions, with no adjustments of the settings. Furthermore, the influence of sweat on the skin was
examined and led to the basic principle of having dry skin exposed. The presence of
a sweat layer only slightly modifies the absolute value of $T_{sk}$ and induces a blurry
aspect in the thermogram as reported by Vegthe (1979). Radiation emitted by the
skin through the thin layer of sweat is little affected. The removal of sweat allows
very fine contrasts within a region (0.5°C) to become sharper such as the thinness of
superficial veins.

During clothed investigations, a strict procedure was designed regarding the removal
of all items of the clothing ensemble (Chapter 6 and 7). Lastly, a reference surface
covered by a black mat paint ($\varepsilon \approx 1$) was developed and positioned in each
thermogram so that temperature could be readjusted according to a reference
temperature measured with a calibrated thermistor.

2.3. Pre-experimental test session

All participants were required to attend the Environmental Ergonomics Research
Centre at least one week prior to testing for a sub-maximal fitness test,
anthropometric measurements and a familiarisation with the thermal questionnaires.
An explanation of the experimental procedure and aims were provided at this time as
a reminder of the documents sent to each participant.

2.3.1. Anthropometric measurements

Stature was measured in centimetres (cm) using a stadiometer and body mass
recorded in kilograms (kg) using an electronic scale (Mettler Toledo kcc150, Mettler
Toledo, Leicester, UK, Resolution 1g).

2.3.2. Skinfold Measurements

Skinfofold thickness (SFT) measurements were carried out for all studies on the right
hand side of the body in order to obtain local body fat thickness and predict overall
body fat percentage (%BF). Measurements were taken using Holtain/Whitehouse
skinfold caliper (Holtain Ltd. Crymych, UK). For specific studies, an extensive
procedure is applied to assess fat distribution based on SFT measured at 24 locations.
Standard locations as well as additional locations in line with Edwards (1950) were
implemented in this bodymapping approach of fat thickness. The description of each
SFT measurement is presented in Table (2.1) and a visualisation is shown in Figure
(2.1).
The sum of measurements at a number of specific SFT sites were used to estimate total body density ($D_b$) in grams per cubic centimetre (g.cm$^{-3}$) and then used to derive total %BF based on established relationships. Numerous population-specific equations have been developed for relatively homogeneous populations with similar characteristics such as age, gender, ethnicity or fitness level (Heyward and Wagner, 2004).

Jackson and Pollock (1978) defined an equation (2.1) for male athletes using the sum of seven skinfolds sites (triceps, anterior suprailiac, abdomen, thigh, chest, midaxillary, subscapular).

$$D_b = 1.112 - 0.00043499 \times (\Sigma 7 \text{ SFT}) + 0.00000055 \times (\Sigma 7 \text{ SFT})^2 - 0.00028826 \times (age)$$

(2.1)

Jackson et al. (1980) proposed an equation (2.2) for female athletes using four skinfolds sites (triceps, suprailiac, abdomen, thigh).

$$D_b = 1.096095 - 0.0006952 \times (\Sigma 4 \text{ SFT}) + 0.00000011 \times (\Sigma 4 \text{ SFT})^2 - 0.0000714 \times (age)$$

(2.2)

Populations of untrained participants require different equations for the calculation of body density due to their different subcutaneous and internal fat distribution (Heyward and Wagner, 2004). Jackson and Pollock (1978) have obtained the following equation for untrained males using the sum of 3 skinfold sites (chest, thigh and abdomen).

$$D_b = 1.109380 - 0.0008267 \times (\Sigma 3 \text{ SFT}) + 0.00000016 \times (\Sigma 3 \text{ SFT})^2 - 0.0002574 \times (age)$$

(2.3)

Jackson et al. (1980) proposed an equation (2.2) for untrained females using the sum three skinfolds sites (triceps, suprailiac, thigh).

$$D_b = 1.0994921 - 0.0009929 \times (\Sigma 3 \text{ SFT}) + 0.00000023 \times (\Sigma 3 \text{ SFT})^2 - 0.0001392 \times (age)$$

(2.4)

Following the calculation of $D_b$, %BF was calculated using Siri’s equations (Siri, 1956) distinct for males and females as shown in equation (2.5) and (2.6):

$$BF \, (\%) = \left( \frac{0.495}{D_b - 4.50} \right) \times 100$$

(2.5)

$$BF \, (\%) = \left( \frac{0.501}{D_b - 4.57} \right) \times 100$$

(2.6)

The equations developed by Siri allow the calculation of %BF based upon constants for the density of different body tissues.
<table>
<thead>
<tr>
<th>#</th>
<th>name</th>
<th>direction</th>
<th>description</th>
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<tbody>
<tr>
<td>1</td>
<td>forearm ant.</td>
<td>vertical</td>
<td>2 cm towards the wrist</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fold is lifted over belly of the biceps brachii at the level marked for the triceps and on line with anterior border of the acromial process and the antecubital fossa. Caliper is applied 1 cm below fingers</td>
</tr>
<tr>
<td>2</td>
<td>biceps</td>
<td>vertical</td>
<td>halfway between the acromion process and the anterior axillary fold</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fold is lifted over belly of the biceps brachii at the level marked for the triceps and on line with anterior border of the acromial process and the antecubital fossa. Caliper is applied 1 cm below fingers</td>
</tr>
<tr>
<td>3</td>
<td>shoulder</td>
<td>diagonal</td>
<td>1/3 on the line between the suprasternal notch and the anterior axillary fold</td>
</tr>
<tr>
<td>4</td>
<td>clavicular</td>
<td>oblique</td>
<td>Intersection midclavicular line / line between anterior axillary fold and suprasternal notch (2/3)</td>
</tr>
<tr>
<td>5</td>
<td>pectoral</td>
<td>oblique</td>
<td>halfway anterior axillary line and nipple for men and 1/3 distance for women</td>
</tr>
<tr>
<td>6</td>
<td>chest</td>
<td>oblique</td>
<td>halfway anterior axillary line and nipple for men and 1/3 distance for women</td>
</tr>
<tr>
<td>7</td>
<td>nipple</td>
<td>horizontal</td>
<td>2 cm from the nipple towards the mid sternal line</td>
</tr>
<tr>
<td>8</td>
<td>midaxillary</td>
<td>vertical</td>
<td>Fold is taken at level of xiphoid process along the midaxillary line</td>
</tr>
<tr>
<td>9</td>
<td>upper abdominal</td>
<td>horizontal</td>
<td>Halfway between the nipple and the umbilicus</td>
</tr>
<tr>
<td>10</td>
<td>external oblique</td>
<td>horizontal</td>
<td>Below the lunea semilunaris and on the midclavicular line (under the last rib - take a deep breath)</td>
</tr>
<tr>
<td>11</td>
<td>suprailiac</td>
<td>diagonal</td>
<td>Fold is taken diagonally above the iliac crest along the anterior axillary line</td>
</tr>
<tr>
<td>12</td>
<td>abdominal</td>
<td>vertical</td>
<td>2 cm lateral to the umbilicus</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fold is lifted on anterior aspect of thigh midway between inguinal crease and proximal border of patella. Body weight is shifted to left foot and calliper is applied 1 cm below fingers OR right heel on left toes</td>
</tr>
<tr>
<td>13</td>
<td>thigh</td>
<td>vertical</td>
<td>2 cm proximal to the proximal edge of the patella Body weight shifted to the other foot 1 cm distal to the fingers holding the fold</td>
</tr>
<tr>
<td>14</td>
<td>suprapatellar</td>
<td>vertical</td>
<td>1 cm above marked line on posterior aspect of arm.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fold is taken in the midline of the posterior aspect of the forearm at the level of maximal circumference</td>
</tr>
<tr>
<td>15</td>
<td>forearm post</td>
<td>vertical</td>
<td>Lateral projection of acromial process - inferior margin of olecranon process. Elbow flexed at 90° using a tape measure. Midpoint is marked on the lateral side of arm. Fold is lifted</td>
</tr>
<tr>
<td>16</td>
<td>triceps</td>
<td>vertical</td>
<td>at the level of the cervical spine 4</td>
</tr>
<tr>
<td>17</td>
<td>neck</td>
<td>vertical</td>
<td>2 cm next to the acromion process toward the neck</td>
</tr>
<tr>
<td>18</td>
<td>suprascapular</td>
<td>oblique</td>
<td>Halfway between the axillary fold and the cervical spine seven</td>
</tr>
<tr>
<td>19</td>
<td>scapular</td>
<td>oblique</td>
<td>Vertebral border and inferior angle of scapula on a diagonal line</td>
</tr>
<tr>
<td>20</td>
<td>subscapular</td>
<td>oblique</td>
<td>Halfway from the spine 2 cm below the level of the triceps</td>
</tr>
<tr>
<td>21</td>
<td>infra scapular</td>
<td>vertical</td>
<td>Halfway from the spine at the waist circumference level (narrowest part)</td>
</tr>
<tr>
<td>22</td>
<td>lumbar</td>
<td>vertical</td>
<td>Halfway from the spine at the abdominal circumference level (iliac crest)</td>
</tr>
<tr>
<td>23</td>
<td>lumbo sacral</td>
<td>horizontal</td>
<td>Halfway from the spine at the abdominal circumference level (iliac crest)</td>
</tr>
<tr>
<td>24</td>
<td>calf</td>
<td>vertical</td>
<td>On the medial aspect of the long axis of the calf, slightly proximal to the marked site</td>
</tr>
</tbody>
</table>
Figure 2.1. Location of skinfold measurements over the whole body
2.3.3. Sub-maximal fitness test

An estimation of aerobic fitness level, expressed as maximal oxygen uptake ($\dot{V}O_{2,\text{max}}$), is calculated from a sub-maximal fitness test based on the Åstrand-Ryhming method (ACSM, 2006). Depending on the protocol, the sub-maximal test is conducted either on a treadmill (h/p cosmos mercury 4.0, h/p/cosmos sports & medical gmbh, Nussdorf-Traunstein, Germany), a cycle ergometer (Monark, Copenhagen, Denmark) or a rowing ergometer (Concept 2, model DPM3, Concept 2 Ltd, Wilford, UK) in a 19-20°C environment. Measurement of $T_a$ and $rh$ are taken using a Vaisala HMP35DGT sensor (Vaisala, Helsinki, Finland). HR was monitored using a Polar RS600 monitor (Polar Electro Oy, Kempele, Finland) and recorded at 5 seconds intervals. The sub-maximal fitness test is an incremental exercise with four stages each lasting five minutes. Starting workload was adjusted according to the participant’s knowledge of his/her physical fitness level and corresponded at the lowest to 7 km.h$^{-1}$ for running, 75W for cycling and 100W for rowing. Every five minutes increments were 1.5 km.h$^{-1}$, 25W and 25W respectively. HR measured during the last minute of each steady state stage was plotted against work rate and then extrapolated to the age-predicted maximal HR (220-age). A vertical line was dropped to the x-axis to estimate the workload that could have been achieved. $\dot{V}O_{2,\text{max}}$ was estimated from the predicted maximal workload using activity-specific equations (American College of Sports Medicine, 2006).

**Running** : $\dot{V}O_2$ (mL.kg$^{-1}$.min$^{-1}$) = (0.2*S) + (0.9*S*G) + 3.5  \hspace{1cm} (2.7)

where $S$ = speed in (m.min$^{-1}$), $G$ = gradient of the treadmill (fraction)

**Cycling** : $\dot{V}O_2$ (mL.kg$^{-1}$.min$^{-1}$) = (1.8*W)/m + 7  \hspace{1cm} (2.8)

where $W$ = work rate (kg.m$^{-1}$.min$^{-1}$), $m$ = body mass (kg)

2.4. Generic Skin temperature mapping protocol

This section describes the generic mapping procedure that remained identical for all experimental protocols. Specificities of each $T_{sk}$ mapping protocol will be discussed in the relevant chapters with main differences in terms of exercise type, protocol chronology and duration, population and environmental conditions.
2.4.1. Experimental Set Up
Participants were advised to avoid alcoholic consumption and strenuous exercise within 24 hours prior to testing. They were also requested to abstain from the use of deodorants on the day of the session.
Before participant’s arrival, the different measuring devices were synchronised using the main investigator’s watch. Body mass was recorded at the beginning and end of each experimental session using an electronic scale (Mettler Toledo kcc150, Mettler Toledo, Leicester, UK, Resolution 1g) in a preparation room at a 19-21°C ambient temperature.

2.4.2. Core temperature measurement
$T_{\text{core}}$ was assessed throughout this research using rectal temperature ($T_{\text{re}}$). Following instructions, participants were asked to insert a rectal thermistor (Grant Instruments, Cambridge, UK) 10cm beyond the anal sphincter. The proximal end of the thermistor is terminated with a 14mm plastic bead (The Bead Shop, Manchester, UK). The bead prevented the risk of the probe dislodging during exercise. The rectal probe was then connected onto a data logger (1000 series Squirrel Eltek/Grant, Grant Instruments, Cambridge, UK) and participants remain in the preparation room for 10 minutes to allow for stabilisation of the thermistor.

2.4.3. Clothing
Clothing for all experiments were standardised for all participants. They were always provided with swimming trunks (Tribord, Decathlon, Villeneuve d’Ascq, France) for males and low-cut running shorts and sports bras (Kalenji, Decathlon, Villeneuve d’Ascq, France) for females. Participants were requested to bring their own personal pair of socks and trainers. In Chapter 3, 4 and 5, they were minimally clothed and in Chapter 6 and 7 they were wearing standard full clothing ensemble including gloves and headband. All items of equipment were weighed before and after the session.

2.4.4. Environmental conditions
Environmental temperatures vary between studies from 5°C to 20°C. Based on the psychometric chart, $rh$ levels were adjusted so that the water vapour pressure content remains constant. Experiments were conducted in a controlled climatic chamber (TIS services, Medstead, Hampshire) with $T_a$ and $rh$ measured using a Vaisala HMP35DGT sensor (Vaisala, Helsinki, Finland) and recorded at one minute intervals.
using a 1000 series Squirrel data logger (Grant Instruments, Cambridge, England). For some studies, a vertical panel of three 50cm diameter fans (JS Humidifiers, Littlhampton, UK) was placed 10 cm away from the extremity of the treadmill or rowing ergometer, which corresponds to a distance of 1 meter from the exercising participant. Regular calibration of air velocity was performed using a hot-wire anemometer (model TSI Alnor 8455, TSI Instruments Ltd, High Wycombe, UK; range 0.125-50m.s\(^{-1}\)) at the chest level on the treadmill (1.3m) or the rowing ergometer (0.7m).

**2.4.5. Fluid consumption**

Water was provided in a sports drink bottle which is weighed at the start and end of each experimental session. Participants could drink freely throughout the experiment and were advised to do so in order to avoid dehydration.

**2.4.6. Heart rate monitoring**

HR was monitored using a Polar RS600 monitor (Polar Electro Oy, Kempele, Finland) at specific time points of the session for 2-min periods. This specific discontinuous procedure was designed to overcome the interference of the belt with heat exchanges between the skin and the environment. A thermal signature of the heart rate belt would have been visible on infrared thermograms due to the added insulation if continuously worn. The HR belt was typically removed 5 to 10 minutes before infrared measurements. In the preparation room, before the trial, participants were familiarised with the technique of removal and positioning of the HR belt.

**2.4.7. Subjective evaluation**

Perceptual responses of body thermal state were obtained using three different thermal scales.

Thermal sensation, thermal comfort and wetness sensation scales corresponded to modified scales used by Gagge *et al.* (1969) and Bakkevig and Nielsen (1995) also in the context of exercise. They were in agreement with the instructions from the ISO 10551 (1995).

The perceptual scale of **thermal sensation (TS)** was a 21-degree two-pole scale from *extremely cold* to *extremely hot* (Fig 2.2). It corresponds to an extension of the widely used 7-degree two-pole ISO scale. Each degree in the scale was split into 2 degrees so that fine differences could be reported (e.g. +2 “slightly warm”, +4
“warm”, +3 being a score between +2 and +4, Fig. 2.2).

The evaluative scale for **thermal comfort** (TC) was similar to 4-degree one-pole ISO scale with a point of origin corresponding to comfort. The scale was doubled for each degree and consists of 7 degrees from 0 to -6 with the same descriptors used by Gagge (1969) from **comfortable** to **very uncomfortable** (Fig. 2.2).

Local thermal sensation (TS\textsubscript{local}) and comfort (TC\textsubscript{local}) were obtained from eleven body regions, five anterior body parts (Chest, Abdomen, Anterior arms, Palmar hand, Anterior legs), five posterior body parts (Upper back, Lower back, Posterior arms, Posterior legs) and the face.

The local discomfort votes could reveal a quantitative determinism of thermal discomfort associated with the number of body regions considered as unpleasant. They also suggest a qualitative determinism of discomfort with certain body surfaces taking more or less importance in the expression of cold or warm discomfort (Pellerin et al., 2004).

The **wetness sensation** (WS) scale was an extension of the scale used by Gagge *et al.* (1969) with a 6-degree one pole scale from **dry** to **dripping wet** (Fig. 2.2).

As suggested by ISO10551, the data obtained from the bipolar thermal sensation scale could be considered as continuous data and therefore treated with parametric statistical tests. Non parametric tests were used for thermal comfort and wetness sensation.

**Perceived exertion** (RPE) was measured on a 15-degree Borg rating of perceived exertion scale (from 6 to 20, Borg, 1970).

The administration of all scales always preceded a set of infrared measurement and participants reported their subjective ratings verbally whilst exercising. The scales are presented in Figure 2.2.
Figure 2.2. Scales used for subjective thermal and perceptual evaluation during each experimental session.
2.5. Infrared imaging procedure

Most studies using infrared imaging in the area of thermal physiology have only reported quantitative values of $T_{sk}$ (in tables) with a limited number of regions of interests (ROI). Furthermore, they often presented an “example” thermogram of one individual so called representative of the whole population.

The challenge of the procedure development for this thesis was therefore two-fold:

- firstly to provide a quantitative analysis of the thermograms with ROI over the whole-body
- secondly to provide a unique representation of the $T_{sk}$ spatial distribution (thermal pattern) representative of the whole population and visually accessible with a colour scale

The idea of producing an average thermal pattern is not novel as two teams of researchers already presented in the 1970’s the spatial characteristics of the $T_{sk}$ distribution on a human body shape based on infrared thermography of 4 subjects after immersion (Wade and Veghte, 1977; Hayward and Keatinge, 1981).

![Figure removed due to copyright](image)

**Figure 2.3.** Thermal patterns from Wade and Vegthe (1977)

Improvements in image processing technology further advance this pioneering work by combining individual thermograms digitally and therefore avoid a visual evaluation and manual drawing of the different $T_{sk}$ isotherms (areas comprising predefined ranges of $T_{sk}$).
The present procedure for $T_{sk}$ mapping relies on two main equipments, an infrared camera for image acquisition and a numerical computing software package for image processing.

2.5.1. Infrared thermal camera

The infrared camera used throughout this research work was a ThermaCam B2 (FLIR Systems Ltd, West Malling, Kent, UK). This model corresponded to an affordable option in order to measure temperatures in a -20°C to +55°C range which easily encompasses the normal range of human body $T_{sk}$. The spectral range is 7.3 to 13 µm (far infrared) which also covers the wavelength band at which the emission of human body radiation is maximal according to Wien’s displacement law (2.9)

$$\lambda_{\text{max}} (\mu m) = \frac{2898}{T}$$  (2.9)

Where:

- $\lambda_{\text{max}}$ is the peak wavelength for a given object temperature
- $T$ is the temperature in Kelvin ($K = ^\circ C + 273.15$)

$T_{sk}$ values of 8°C and 36°C correspond respectively to a $\lambda_{\text{max}}$ of 10.3 and 9.4µm. This means that the camera’s detector can sense the peak amount of radiation emitted by the human body.

The camera accuracy is specified as ±2°C which is relatively low compared to the common accuracy of the contact methods (±0.5 to ±0.1°C). A specific element of additional calibration was therefore included in the procedure to overcome this drawback (see 2.5.2).

Despite the low accuracy, the crucial advantage of the thermal camera is its very high thermal sensitivity ±0.1°C. This feature allowed the detection of very small temporal and spatial $T_{sk}$ variations over the body surface on top of having a clear, noise-free quality image. In a body-mapping approach, a highly sensitive camera was therefore the best device to obtain a detailed spatial definition of $T_{sk}$ distribution. It is yet worth noting that the human body is not completely flat and its geometry may hinder the quality of the measurement. As highlighted by Watmough et al. (1970), apparent temperature differences in thermograms arising from the curvature of anatomical surfaces will be negligibly small for obliquity angles less than 45°. This implied that care must be taken regarding the position of the body when performing infrared
imaging (see 2.5.2) and that image processing should take into consideration some edge-effect especially in the upper and lower limbs (see 2.5.3).

The FLIR ThermaCAM B2 possesses a rather low resolution of 160*120 pixels as compared to most advanced and recent expensive cameras (1280*1240 pixels). This was however sufficient for our body mapping purpose.

Although the ThermaCAM B2 was originally designed for the building industry with its excellent handling ease, this camera has been proven useful for physiological research (Havenith et al., 2008a, b, Smith et al., 2011) especially thanks to its high thermal sensitivity.

2.5.2. Image acquisition

A standardised procedure was adopted for the first study and kept consistent throughout this research work. It was initially decided that an anatomical position should serve as a reference for all thermograms, similar to the representations by Wade and Veghte (1977) (see Figure 2.3). Based on surface anatomy, a clear distinction was made between the regions of interest (ROI) of the anterior and posterior human body parts.

Considering the camera resolution, the best option was to perform separate measurement of the main body parts (1 Anterior Upper Body, 2 Posterior Upper Body, 3 Anterior Lower Body and 4 Posterior Lower Body) in the coronal plane (frontal view). An additional thermogram (5 Side) was also obtained in the sagital plane (lateral view) to depict the area from the apex of the axilla (armpit) to the iliac region (Figure 2.4). Before each experimental session, the participant was carefully instructed regarding the exact position for infrared imaging using markers taped on the floor and the wall. During the session, the measurement process was always performed in a still position, in a very close proximity to the exercising device.

The field of view of the camera was initially defined so that potentially the tallest and largest person investigated would fit within the frame of the thermogram. Height was adjusted using a tripod with fixed leg lengths and a small table (as seen in Fig. 2.4).
Markers were taped on the floor and on the table for the correct position of the table and the tripod. The table was easily removed for Lower Body thermograms (③ and ④) making the most of the camera handling ease. Distance between the camera lens and the target object (human body) was set at 1.9m. The infrared imaging routine lasted 60 seconds (i.e 12 seconds/thermogram). Pilot studies using infrared thermography and thermistors revealed that there was no change in the thermal pattern within the one-minute routine (for each body region) and that changes in absolute $T_{sk}$ were negligible (within 0.5°C). A standardised sequence was then adopted (from ① to ⑤).

A reference surface for calibration was included in the background of each thermogram so that the measurement error could be reduced (infrared camera accuracy ±2°C) to an accuracy of ±0.1°C (similar to that of thermistors). The so-called reference plate consisted of a wooden plate with a square piece of metal (12x12cm) painted with a black matt paint and a crumbled square of aluminium foil next to it (see Figure 2.5). A thermistor (Grant Instruments, Cambridge, UK) was taped to the surface of the black plate and plugged onto a 1000 series Squirrel data logger (Grant Instruments, Cambridge, England). Surface temperature was recorded at one-minute intervals. Temperature values were then compared between the contact (thermistor calibrated against a mercury thermometer in a water bath) and the non-contact method (IR thermography) over a similar surface with the thermistor reading serving as a reference for recalibration. On average, the correction applied to a thermogram was around 0.5°C with this method, IR readings being lower than thermistor readings.
Figure 2.5. Digital and infrared pictures of identical views for the imaging sequence (① Anterior Upper Body, ② Posterior Upper Body, ③ Anterior Lower Body and ④ Posterior Lower Body, ⑤ Side).
N.B Pictures not taken at the same time. However, the image processing program could take these slight changes in position into account.
The crumbled piece of aluminium foil was useful for the estimation of the “reflected temperature” following the manufacturer’s instructions in order to take radiative elements of the environment into account.

2.5.3. Image pre-processing

The camera receives three different types of radiation:

1- Emission of the object ($\varepsilon \tau W_{obj}$).

The emission collected by the camera is a function of the object emissivity and the transmittance $\tau$ of the atmosphere. It highly depends upon the emissivity $\varepsilon$ of the object. The human skin acts as a graybody ($\varepsilon < 1$) and has been defined by Steketee (1973) with $\varepsilon = 0.98$. The total radiant emittance of a graybody is defined by the Stefan-Boltzmann formula (2.10)

$$W_{obj} = \varepsilon \sigma T^4 \quad (2.10)$$

where $W_{obj}$ = total radiant emittance of the object (W.m$^{-2}$), $\varepsilon$ = emissivity of the object, $\sigma$ = Stefan-Boltzman constant ($5.67 \times 10^{-8}$ W.m$^{-2}$.K$^{-4}$), $T$ = temperature of the object (in K).

2- Reflected emission from ambient sources ($(1-\varepsilon) \tau W_{refl}$)

The emission collected by the camera is a function of the reflectance of the object (1- $\varepsilon$), the transmittance $\tau$ of the atmosphere. Ambient sources have the temperature $T_{refl}$ which is considered the same for all emitting surfaces within the halfsphere seen from a point on the object surface.

3- Emission from the atmosphere ($(1-\tau) W_{atm}$)

The emissivity of the atmosphere is defined as (1- $\tau$) and the total emission will depend on the atmosphere temperature ($T_{atm}$).

The three different radiation terms are illustrated in Figure 2.6. The camera output voltage obtained with the uncooled microbolometer detector (based on all emissions) can then be converted into $T$ (in our case $T_{sk}$) providing parameters involved in the above emissions are known for the calculation.

Within the three emissions described, the emission of the object is the most important considering the controlled laboratory environment where the influences of external radiation and the atmosphere characteristics are negligible. The radiation of the object largely depends on the emissivity coefficient at a given surface temperature, especially considering the exponential in the equation.
The following five parameters are required for image pre-processing:

- object emissivity ($\varepsilon$)
- relative humidity ($rh$)
- atmosphere temperature ($T_{atm}$ or $T_a$)
- object distance ($D_{obj}$)
- reflected ambient temperature ($T_{refl}$)

Fixed values are used for skin emissivity ($\varepsilon = 0.98$) and object distance is consistently kept at 1.9m whereas $rh$ and $T_a$ are continuously recorded in the climatic chamber and provided for each thermogram thanks to the synchronisation between the datalogger and ThermaCamB2.

Image pre-processing is performed using FLIR ThermaCam Researcher Pro 2.8 (FLIR Systems Ltd., West Malling, Kent, UK) where the different parameters are implemented for each thermogram. The software is also used to estimate reflected ambient temperature ($T_{refl}$) on the thermogram. A calibration value is then obtained by comparing the reference plate’s surface temperature on the thermogram with the synchronised thermistor recording. Lastly, the fully adjusted thermogram is saved as a matlab file (.mat) for the actual image processing.
2.5.4. Image processing

A novel procedure of image processing was developed in order to standardise the analysis of numerous thermograms as well as to exploit the important spatial information of each individual thermogram. This project was initiated after discussions with experts in the field at Glamorgan University (Dr Ricardo Vardasca, Dpt. of Medical Imaging) and Loughborough University (Dr David Kerr, Dpt of Optical Engineering). The development of the image processing procedure was then performed on a self-taught basis under MATLAB 7.8.0 (MATLAB R2009a, The MathWorks Inc., Natick, USA). In the end, this procedure managed to produce two main outcomes:

- $T_{sk}$ values for a pre-defined and standard segmentation of the human body
- Average body maps of $T_{sk}$ distribution representative of the studied population

The advantage of this imaging procedure lies in the dual use of the processing technique called *image registration*. The latter involved the selection of control points (CP) on the image prior to an image transformation based on the CP coordinates. In this project, image registration was useful for both the achievement of a pre-defined segmentation and the creation of $T_{sk}$ body maps.

Thresholding methods have been originally disregarded as they would have only given the outline of the body shape with no defined regions and no possibility for transformation. Moreover, the automatic determination of threshold values may have been problematic for each individual, especially with the edge-effect problems.

A detection of reflective markers on the human body would have been possible (similar to motion analysis) but this was deemed risky with the problems of sensors falling off due to wet skin and motion, the difficult feasibility with clothed subjects on top of the time consuming subject preparation.

For these reasons, a manual selection of CP was preferred digitally on the pre-processed thermogram with standard anatomical landmarks around the body contour. This was considered as the best option despite its time-consuming nature. The embedded `cpselect` function in the MATLAB image analysis toolbox allowed the selection of CP on individual thermograms next to the reference thermogram (Figure 2.7). The locations of all the different anatomical landmarks are presented in Figure 2.8 together with the whole-body segmentation and associated labels.
Image registration was designed for the development of whole-body segmentation, different from the existing segmentation using IR thermography (Jansky et al., 2003, Zaidi et al., 2010, Zaproudina et al., 2008). The core idea was to define regions closely related to large muscle groups (e.g. pectorals, quadriceps) insofar as the influence of active muscles was included in the scope of the present research. These regions were also defined so that specific areas encompassed skinfold sites and combined regions also corresponded to the local evaluation in terms of thermal sensation and comfort (e.g. abdomen, anterior arms) (see 2.6). Selection of CP was performed by visual observation of the experimenter 2 pixels into the body contour so that no background pixels could be accidentally misinterpreted and analysed as a pixel representing $T_{sk}$. This issue is particularly true in the limbs where the curvature effect is more pronounced. Watmough (1970) indicated that apparent differences in thermograms arising from curvature of anatomical surfaces will be negligible for obliquity angles less than 45°C.

On top of the manually selected CP, additional landmarks were computed using spatial geometry (coordinates of the intersections between straight lines joining 2 CP) in order to help the definition of these specific regions.

Regional temperature data were then automatically computed (regionprops function) from each of the 52 regions, i.e. average $T_{sk}$, median $T_{sk}$, minimal $T_{sk}$, maximal $T_{sk}$, standard deviation.
$\bar{T}_{sk}$ was calculated as the average of all pixels over the recorded body surface, excluding the covered body parts (groin, feet, scalp) similar to the procedure used by Choi et al. (1997) and Zaidi et al. (2007). This was done after a correction of the matrix values from Kelvin into degrees Celsius and the recalibration of each pre-processed thermogram with the correction values (difference between IR and thermistor readings on the reference plate).
Figure 2.8. Whole-body segmentation based on five thermograms (①to⑤) and corresponding labels in table.

<table>
<thead>
<tr>
<th>No.</th>
<th>Region</th>
<th>No.</th>
<th>Region</th>
<th>No.</th>
<th>Region</th>
<th>No.</th>
<th>Region</th>
<th>No.</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>R. Lower Arm</td>
<td>16</td>
<td>L. Hypochondriac</td>
<td>31</td>
<td>Mid Upper Back</td>
<td>46</td>
<td>L. Hamstrings</td>
<td>47</td>
<td>R. Hamstrings</td>
</tr>
<tr>
<td>2</td>
<td>R. Volar Elbow</td>
<td>17</td>
<td>R. Lumbar</td>
<td>32</td>
<td>R. Infrascapular</td>
<td>48</td>
<td>R. Knee</td>
<td>49</td>
<td>R. Calf</td>
</tr>
<tr>
<td>3</td>
<td>R. Biceps</td>
<td>18</td>
<td>Umbilical</td>
<td>33</td>
<td>L. Hip</td>
<td>50</td>
<td>L. Back hand</td>
<td>51</td>
<td>R. Back hand</td>
</tr>
<tr>
<td>4</td>
<td>R. Shoulder</td>
<td>19</td>
<td>L. Lumbar</td>
<td>34</td>
<td>Lower Back</td>
<td>52</td>
<td>Lower Abdomen</td>
<td>53</td>
<td>Upper Abdomen</td>
</tr>
<tr>
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<td>R. Pectoral</td>
<td>20</td>
<td>Face</td>
<td>35</td>
<td>R. Hip</td>
<td>54</td>
<td>Chest</td>
<td>55</td>
<td>Armpit</td>
</tr>
<tr>
<td>6</td>
<td>L. Pectoral</td>
<td>21</td>
<td>L. Lower Arm post</td>
<td>36</td>
<td>R. Shin</td>
<td>56</td>
<td>Scapular</td>
<td>57</td>
<td>Cheek</td>
</tr>
<tr>
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<td>R. Clavicular</td>
<td>22</td>
<td>L. Dorsal Elbow</td>
<td>37</td>
<td>R. Patella</td>
<td>58</td>
<td>Upper Arm back</td>
<td></td>
<td></td>
</tr>
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<td>Throat</td>
<td>23</td>
<td>L. Triceps</td>
<td>38</td>
<td>R. Thigh</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>L. Clavicular</td>
<td>24</td>
<td>L. Scapular</td>
<td>39</td>
<td>L. Thigh</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>L. Shoulder</td>
<td>25</td>
<td>Upper Back</td>
<td>40</td>
<td>L. Patella</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>L. Biceps</td>
<td>26</td>
<td>R. Scapular</td>
<td>41</td>
<td>L. Shin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>L. Volar Elbow</td>
<td>27</td>
<td>R. Triceps</td>
<td>42</td>
<td>R. Palm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>L. Lower Arm</td>
<td>28</td>
<td>R. Dorsal Elbow</td>
<td>43</td>
<td>L. Palm</td>
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<td>R. Hypochondriac</td>
<td>29</td>
<td>L. Lower Arm post</td>
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<td>L. Calf</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>15</td>
<td>Epigastric</td>
<td>30</td>
<td>L. Infrascapular</td>
<td>45</td>
<td>L. Knee</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The second phase of the image processing procedure was the *image transformation* (morphing). To account for between-subject differences in body size and shape, all thermograms were morphed (i.e. projected) onto a reference body shape chosen as a male and female with median characteristics of the group (height, body mass, body fat). Morphing was performed based on the CP coordinates of the input thermogram and the reference thermogram via a landmark-based algorithm operating a 3rd order polynomial transformation. The algorithm was launched from the *cp2tform* and *imtransform* function embedded in the MATLAB image analysis toolbox. The morphing process was repeated for each thermogram separately after selection of CP so that the $T_{sk}$ spatial information was translated into the standard body shape. The individual morphed thermograms were then averaged to obtain a final body map of $T_{sk}$ distribution, representative of the whole population studied. Figure 2.9 summarises the different stages of the image processing procedure.

![Image processing sequence using MATLAB combining individual thermograms for the creation of an average body map of $T_{sk}$ distribution](image)

A detailed user manual (French/English) has been developed to describe the step by step procedure from infrared measurements to the creation of whole-body $T_{sk}$ maps. It is important to mention that quantitative $T_{sk}$ values (from the segmentation in Fig. 2.8) were obtained before morphing (based on the original image) and that morphing induced a $\pm 15\%$ constriction or dilation in effective body pixel count from morphed vs original thermogram. The morphed image solely impacted the topographical representation for the final average map. The author has performed several adjustments to find the optimal number of CP for the most suitable morphing procedure, though this has not been the topic of a specific reproducibility study (inter or intra-experimenter). The same experimenter (i.e the author) has performed the analysis of all the dataset (a total of 1 800 thermograms and 53 000 CP for the whole present thesis).
2.6. Analysis

2.6.1. Gross Sweat Loss

Gross sweat loss (GSL) was calculated based on the weight change of each participant across each test period and adjusted for fluid intake, either absolute (g) or relative to the surface area and the time duration (g.m\(^{-2}\).h\(^{-1}\)).

\[
\text{GSL}(g) = w_{b1} - w_{b2} + \text{fluid} 
\]

\[
\text{GSL (g.m}^{-2}.\text{h}^{-1}) = \frac{\left( w_{b1} - w_{b2} + \text{fluid} \right)}{t} \cdot AD \cdot 3600
\]

Where:

- \(w_{b1}\) body mass at start of experiment (g)
- \(w_{b2}\) body mass at end of experiment (g)
- fluid total fluid consumption (g)
- \(t\) time duration (s)
- \(AD\) surface area (m\(^2\))

Corrections were made for respiratory and metabolic mass loss based on the equations described by Livingstone et al. (1994) and Bakkevig and Nielsen (1995).

2.6.2. Whole-body maps of T\(_{sk}\) distribution

The image processing procedure offered a visualisation of body maps combining all the available thermograms of a group or combining selected individuals with appropriate intra-groups.

Body maps of T\(_{sk}\) distribution were produced at selected time points for each protocol allowing a comparison of the thermal patterns over time or between studies.

Once all the thermograms have been processed and morphed, different types of body maps can easily be created (Fig. 2.10):

- **Map of absolute T\(_{sk}\) (A):** average of several morphed thermograms
- **Map of relative T\(_{sk}\) (B):** absolute map of a population divided by the population-
  \(\bar{T}_{sk}\) (every matrix pixel) at the relevant stage
- **Map of standard deviation (C):** standard deviation of every matrix pixel based on all individual absolute morphed thermograms and the group-
  \(\bar{T}_{sk}\)
- **Map of T\(_{sk}\) difference (D):** absolute map\(_a\) – absolute map\(_b\) (a and b being different time stages of the same protocol or similar stages of different protocols)
The colour coded scales are either a default colormap built in MATLAB© (A, C, D) or a specifically custom-made colour scale (B) as explained in Appendix C.

2.6.3. Local parameters

Part of the research investigated the various relationships between regional information. Bodymapping of fat distribution offered a good way to analyse the relationships between local $T_{sk}$ ($T_{sk,local}$) and local skinfold thickness ($SFT_{local}$). The relationships were analysed following two approaches:

- *Between-subject approach*: investigating a single body region with corresponding data for all participants (inter-individual variability)
- *Within-subject approach*: investigating several regions using averaged values for all participants of each body region ($T_{sk,local}$ and $SFT_{local}$) (intra-individual variability)

Corresponding regions are organised as follow (see Figure 2.8 for $T_{sk}$ regions). SFT values were averaged when several sites corresponded to the same $T_{sk}$ region.

<table>
<thead>
<tr>
<th>$T_{sk}$ region</th>
<th>Skinfold site(s)</th>
<th>$T_{sk}$ region</th>
<th>Skinfold site(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Forearm anterior</td>
<td>38</td>
<td>Thigh</td>
</tr>
<tr>
<td>3</td>
<td>Biceps</td>
<td>37</td>
<td>Suprapatellar</td>
</tr>
<tr>
<td>4</td>
<td>Shoulder</td>
<td>29</td>
<td>Forearm posterior</td>
</tr>
<tr>
<td>5</td>
<td>Clavicular</td>
<td>27</td>
<td>Triceps</td>
</tr>
<tr>
<td>7</td>
<td>Pectoral, chest, nipple</td>
<td>25</td>
<td>Neck, Suprascapular</td>
</tr>
<tr>
<td>14</td>
<td>Midaxillary</td>
<td>26</td>
<td>Scapular</td>
</tr>
<tr>
<td>15</td>
<td>Upper abdominal</td>
<td>32</td>
<td>Subcapular, Infra-Scapular</td>
</tr>
<tr>
<td>17</td>
<td>External oblique, supra-iliac</td>
<td>35</td>
<td>Lumbar, Lumbosacral</td>
</tr>
<tr>
<td>18</td>
<td>Abdominal</td>
<td>36</td>
<td>Calf</td>
</tr>
</tbody>
</table>

Several $T_{sk}$ regions were averaged so that corresponding body parts could be analysed in terms of $T_{sk,local}$ and local thermal votes ($T_{S_{local}}$ and $T_{C_{local}}$).
**2.6.4. Body temperatures**

Mean body temperature (\( \bar{T}_b \)) was calculated from \( T_{re} \) and \( T_{sk} \) and using the equation (2.11) assuming a state of vasoconstriction in the cold environment (Parsons, 2003):

\[
\bar{T}_b = 0.67 \, T_{re} + 0.33 \, T_{sk}
\]  

(2.11)

The state of vasoconstriction will however be discussed in the various chapters where appropriate as the exercising situations potentially modified the vasomotor state of the body. The proportion between the “shell” and the “core” is rarely constant, especially in the context of exercise in the cold. A fixed calculation was yet chosen to be in line with similar studies (e.g. Nielsen and Nielsen, 1984).

**2.6.5. Statistical Analysis**

Statistical analysis was performed using SPSS (version 18.0, Chicago, USA). Paired t-tests were performed on all relevant zones and Holm-Bonferroni correction was applied to adjust for multiple comparisons. Local \( T_{sk} \) were analysed for differences between individual regions (or group of regions). Repeated measures ANOVA were performed with post hoc multiple comparisons. Different main factors were analysed according to the protocol. Considering the large number of regions, multiple comparisons were performed with the risk of inflating type I error. It was decided to adjust for multiple comparisons whilst considering the risk of inflating type II error. On balance, both corrected and uncorrected p values were presented. The issue of multiple comparisons and the conservative nature of Holm-Bonferroni correction were recognised during all analyses.

Analysis of the relationship between two variables was assessed using a Pearson’s r correlation. Pearson’s r correlation coefficients were produced for the dependant variable \( T_{sk,local} \) and several independent variables such as \( SFT_{local} \), \( TS_{local} \), \( TC_{local} \) or the dependant variable \( \bar{T}_{sk} \) and %BF or metabolic rate (M).
CHAPTER 3
Sex differences in skin temperature patterns
whilst running at 10°C

Chapter Summary
This first experimental chapter investigates thermal and perceptual responses of a group of lean active males and females whilst running at 10°C. Participants were required to run at 70% $\dot{V}O_{2,max}$ for 40 minutes followed by 10 minutes of post-exercise rest. Infrared thermography measurements were performed throughout the exercise to exhibit sex-differences in skin temperature distribution. A similar pattern of skin temperature was observed between males and females, though absolute regional temperatures were on average 1.6°C lower for females. Specific features in the thermal pattern were highlighted such as a Y-shape of colder temperatures over the anterior torso or a Y-shape of warmer temperature over the posterior torso. The distribution of skinfold thickness was able to explain skin temperature distribution solely for the anterior torso. No sex-differences were found in perceptual responses. The distribution of regional thermal sensations was positively correlated with regional skin temperature distribution at the end of exercise.

3.1. Introduction
Sex differences in thermal response to cold exposure is an area of minimal investigation since the pioneering work of Hardy and DuBois (1940). Most of the research was primarily focused on the impact of cold environments or water immersion on overall response in terms of $T_{core}$ and $T_{sk}$. It is commonly accepted that women maintain a $T_{sk}$ 1 to 2°C lower than men at rest and during exercise in the cold (Graham, 1988). However, the sex influence on the whole-body patterns of $T_{sk}$ distribution has never been explored.
Regarding overall responses, the larger $A_{Du}/M$ of a typical female, favourable for heat dissipation (Kollias et al., 1974), can be offset by differences in heat storage capacity during exercise (Havenith, 2001a). Heat storage capacity depends on body
mass and body composition. On a population level, females have a smaller body mass with a greater percentage of body fat (Sawka and Young, 2000). As fat mass has a lower specific heat compared to lean mass, females will increase or decrease their mean body temperature more for a given change in body heat content (Cheung et al., 2000). During exercise in cold air, men have significantly greater increase in metabolism at the same absolute workload (Graham, 1988).

Regarding local responses, it is suggested that fat thickness may explain to a certain extent the spatial variations of \( T_{sk} \) observed over the body (LeBlanc, 1954). Fat patterning represents an important sexual dimorphism (Mueller, 1985) with a gynoid fat distribution for females (gluteo-femoral regions) and android distribution for males (abdominal and upper body regions). To our knowledge, no studies have investigated the spatial variations of \( T_{sk} \) and skinfold thickness (SFT), neither at rest nor during exercise. Although females tend to have thicker skinfolds locally, tissue insulation is also influenced by superficial layers of muscle when blood perfusion is limited (Veicsteinas et al., 1982; Rennie, 1988) with variations from site to site. Locally, skin circulation largely influences tissue conductance and consequently \( T_{sk} \). No sex differences have been found in skin blood flow through mapping several body regions, though this was performed in a 29°C environment at rest in a semi-nude condition (Park et al., 1997). In cold environments, some authors have reported lesser circulation to the extremities in females (Buskirk et al., 1963; Burse, 1979). The observations of regional skin blood flow in non-acral regions between males and females have not been specifically analysed during exercise in the cold. Locally, males and females have similar sweat distribution patterns with high sweat production along the spine and higher sweat rate on the chest than on the back as a whole (Havenith et al., 2008a). In almost all locations and for the whole-body, females had lower sweat rates compared to males and this has been attributed to differences in the amount of metabolic heat produced at a given relative workload. Locally, heat production from the active muscles has been shown to influence surface temperature via radial convection of blood (Robinson et al., 1965). In males, thermographic evaluations have highlighted that active calves remain warmer than the surrounding body regions (Clark et al., 1977, Vegthe et al., 1979). To the author’s knowledge, the use of infrared thermography has never been published in a study comparing a group of males and females neither at rest nor
during exercise. A description has only been done qualitatively for one semi-nude male and female in the same neutral environment (Clark and Edholm, 1985). Moreover, overall and local subjective votes have to the author’s knowledge never been published during exercise in the cold between sexes. At rest, Parsons (2002) reported few differences between males and females in overall thermal comfort, females tended to feel cooler than men in cool conditions. Comfort equations derived for occupational contexts have inadequate allowance for the weighing of metabolic rate during sport events, especially as light clothing is worn and some degree of thermal discomfort is tolerated (Reilly, 2009).

Based on the above information, it was decided to perform a study comparing male and female $T_{sk}$ responses and their associated perceptual responses during an exercising protocol in the cold.

The sex differences in body fat content (%BF) and local SFT represent an interesting way to evaluate the relative contribution of fat as a passive internal determinant on $T_{sk}$ and its distribution. The association between subjective votes and $T_{sk}$ parameters can also be investigated. It was hypothesized that:

- females will exhibit cooler $T_{sk}$ than males in each body region and overall
- $\bar{T}_{sk}$ will be a function of body fat and metabolic rate
- Local $T_{sk}$ will be negatively correlated with local skinfold thickness
- $T_{sk}$ patterns between males and females will be different due to the gender-specific differences in fat patterning
- Skin surface overlying active muscles will depict warmer temperatures than the surrounding regions in both males and females
- Patterns of $T_{sk}$ distribution will vary between rest and exercise due to the large vasomotor adjustments
- Females will feel cooler than males throughout the protocol
3.2. Methods
The experimental protocol was following the generic procedures presented in Chapter 2 for the specific case of running.

3.2.1. Participants
Nine males and nine females were recruited among the student population and staff of Loughborough University. All participants signed an informed consent after explanation of the study methods and goals. The following inclusion criteria were used:
- Caucasian participants
- Age 18-30 years old
- Physically active and able to run 10 km in less than 70 minutes
- No current injuries/medications

3.2.2. Pre-Test session
The pre-test session involved anthropometric measurements of height and body mass. Extensive skinfold thickness measurements were also performed at 24 locations across the right side of the body. Standard locations as well as additional locations in line with Edwards (1950) were used. The large number of sites gave a finer representation of the distribution of fat thickness so that each site could be associate with a corresponding regional $T_{sk}$. Body density was calculated from 7 measurements of skinfold thickness for males and 3 measurements for females (Jackson and Pollock, 1978) and then converted into percentage body fat (%BF) using Siri’s equation (1956).

The second part of the pre-test session consisted of a sub-maximal fitness test following the guidelines of ACSM (2004) using a running ramp test with 4 increments of 5 minutes with an increase of the running speed by $1.5 \text{ km.h}^{-1}$. The determination of predicted maximal oxygen uptake ($\dot{V}O_{2,\text{max}}$) using ACSM’s equation (2004) allowed the calculation of the estimated running speed and targeted heart rate for the experimental session which corresponded to 70% $\dot{V}O_{2,\text{max}}$.

Participants were familiarised with the subjective scales for thermal sensation and thermal comfort votes (see 2.4.9) during the first stages of the submaximal test. Overall votes (whole-body sensation and comfort) were rated as well as local votes.
of 11 individuals body regions (chest, abdomen, upper back, lower back, anterior arms, posterior arms, anterior legs, posterior legs, palm of hands, dorsal hands, face).

3.2.3. Methodology

All experiments were conducted in a climatic controlled chamber with air temperature set at 10°C and relative humidity set at 50% measured using Vaisala HMP35DGT sensor (Vaisala, Helsinki, Finland) and recorded at 10 seconds intervals using a data logger (Eltek/Grant, 1000 series squirrel, Grant Instruments, Cambridge, UK).

The experimental protocol was designed to reproduce the different stages of a typical running scenario for active regular runners. Exercise intensity was therefore set at 70% \( \dot{VO}_{2,max} \). Four different sets of infrared measurements were taken with the subject standing in an anatomical position: 5 minutes after entering the climatic chamber (PRE), after 10 minutes of running (RUN10), after 40 minutes of running (RUN40) and after 10 minutes of post-exercise recovery standing on the treadmill (POST).

Subjective votes (thermal sensation, thermal comfort, RPE) were preceding the infrared measurements and recorded in the last 2 minutes of each stage.

A vertical panel of three 50cm diameter fans (JS Humidifiers, Littlehampton, UK) was placed 10 cm away from the front of the treadmill, which corresponds to a distance of 1 meter from the running participant. Air flow was turned on only during the running periods and the air velocity was set to match the average running speed of the participants (i.e 2.8 m.s\(^{-1}\)). Regular calibration of air velocity was performed using a hot-wire anemometer (model TSI Alnor 8455, TSI Instruments Ltd, High Wycombe, UK; range 0.125-50m.s\(^{-1}\)) at the chest level (1.3m) on the treadmill. Air flow was turned off before each set of infrared measurements as recommended by Clark and Edholm (1985).

The infrared camera (Thermacam B2, FLIR Systems Ltd, West Malling, Kent, UK, accuracy ± 2°C, thermal sensitivity ± 0.1°C) was fixed on a tripod with adjustable legs at constant lengths regardless of the participant height. Women were asked to remove their bras so that the bare skin could be exposed. Five different thermograms (Anterior Upper Body, Posterior Upper Body, Anterior Lower Body, Posterior Lower Body, Side) were taken in less than 1½ minute.
Heart rate was monitored using a Polar RS600 monitor (Polar Electro Oy, Kempele, Finland). The heart rate belt was removed 5 minutes before infrared measurements to avoid changes in the heat exchanges between the skin and the environment due to the belt.

Rectal temperature ($T_{re}$) was measured with a rectal thermistor (Grant Instruments, Cambridge, UK) connected to a data logger (1000 series Squirrel Eltek/Grant, Grant Instruments, Cambridge, UK). Estimated metabolic rate was calculated using Epstein’s equation (1987) based on body mass and running speed.

### 3.2.4. Experimental protocol

Body and clothing mass were recorded upon arrival at the laboratory and immediately after the session using an electronic scale (Mettler Toledo kcc150, 150kg, Mettler Toledo, Leicester, UK). Gross sweat loss was calculated from body mass loss and water intake, corrected for metabolic and respiratory mass losses.

Males were provided with swimming trunks (Tribord, Decathlon, Villeneuve d’Ascq, France) and females low-cut shorts and bras (Kalenji, Decathlon, Villeneuve d’Ascq, France). Participants were required to wear their own socks and trainers. Following instructions, they were asked to insert a rectal probe (Grant Instruments, Cambridge, UK) terminated with a 14mm plastic bead (The Bead Shop, Manchester, UK) 10cm beyond the anal sphincter. The bead prevented the risk of probe dislodgment during exercise. The rectal thermistor was then connected to a data logger (1000 series Squirrel Eltek/Grant, Grant Instruments, Cambridge, UK). Participants remained in the preparation room for 10 minutes to account for stabilisation of the thermistor. The experimenter and the participants then walked into the climatic chamber and followed the timed procedure as described in Figure 3.1.

![Figure 3.1: Experimental chronology in the climatic chamber. Arrows correspond to the 4 stages for administration of the thermal responses questionnaires followed by infrared imaging](image-url)
3.2.5. Analysis

The infrared images recorded at the 4 different stages of exercise were analysed using the specific imaging procedure described in 2.5.3 including primary image pre-processing (calibration, environmental adjustment under FLIR ThermaCam Research Pro 2.8) and secondary image processing MATLAB 7.8.0. Image registration was used to extract Tsk parameters (min T_{sk}, max T_{sk}, average T_{sk}, median T_{sk}, standard deviation) from a pre-defined segmentation for each thermogram as well as to create whole-body T_{sk} maps (each stage and each group) after morphing of individual thermograms onto a reference body shape. T_{\bar{sk}} was computed using all available body pixels excluding the covered body regions (groin, feet, scalp).

Statistical Analysis was conducted using the Statistical Package for the Social Sciences 16.0 (SPSS Inc, Chicago, IL, USA). A two-way repeated measures ANOVA was used to investigate the main effect of time and sex. Dependent variables were T_{re}, T_{\bar{sk}} and T_{sk,local}.

Holm-Bonferroni corrections were applied to allow for multiple comparisons when comparing the different body regions investigated. A Pearson-correlation coefficient was obtained following regression analysis between T_{sk} parameters (local or overall) and body fat parameters or perceptual parameters (local or overall).

3.3. Results

3.3.1. Participants

The participants’ characteristics and predicted absolute metabolic rate are presented in Table 3.1.

3.3.2. Skinfold thickness

The distribution of adipose tissue thickness is presented for both groups in Table 3.2 and 3.3.
Table 3.1. Participants’ characteristics (mean ± SD) and predicted absolute metabolic rate of the 2 groups during the experimental protocol

<table>
<thead>
<tr>
<th>Participant no</th>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Mass (kg)</th>
<th>( A_D ) (m²)</th>
<th>( A_D/M ) (cm².kg⁻¹)</th>
<th>Body fat content (%)</th>
<th>Sum of skinfolds (mm)</th>
<th>Predicted VO(_{2\text{max}}) (mL.min⁻¹.kg⁻¹)</th>
<th>Treadmill speed (km.h⁻¹)</th>
<th>Absolute Metabolic rate (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>f1</td>
<td>18</td>
<td>174</td>
<td>68.2</td>
<td>1.82</td>
<td>266</td>
<td>21.8</td>
<td>305.7</td>
<td>47.9</td>
<td>9</td>
<td>796</td>
</tr>
<tr>
<td>f2</td>
<td>22</td>
<td>171</td>
<td>58.3</td>
<td>1.68</td>
<td>288</td>
<td>19.2</td>
<td>265.1</td>
<td>50.7</td>
<td>9.6</td>
<td>780</td>
</tr>
<tr>
<td>f3</td>
<td>20</td>
<td>165</td>
<td>63.5</td>
<td>1.70</td>
<td>267</td>
<td>21.8</td>
<td>350.5</td>
<td>53.7</td>
<td>10.2</td>
<td>855</td>
</tr>
<tr>
<td>f4</td>
<td>21</td>
<td>174</td>
<td>72.8</td>
<td>1.87</td>
<td>256</td>
<td>20.1</td>
<td>254.2</td>
<td>46</td>
<td>8.6</td>
<td>791</td>
</tr>
<tr>
<td>f5</td>
<td>20</td>
<td>171</td>
<td>68.6</td>
<td>1.80</td>
<td>262</td>
<td>19.1</td>
<td>288.3</td>
<td>62.3</td>
<td>12</td>
<td>1048</td>
</tr>
<tr>
<td>f6</td>
<td>23</td>
<td>173</td>
<td>68.4</td>
<td>1.81</td>
<td>265</td>
<td>23.1</td>
<td>270.6</td>
<td>50.6</td>
<td>9.6</td>
<td>841</td>
</tr>
<tr>
<td>f7</td>
<td>21</td>
<td>173</td>
<td>73.2</td>
<td>1.86</td>
<td>255</td>
<td>28.1</td>
<td>288.3</td>
<td>50.1</td>
<td>9.5</td>
<td>862</td>
</tr>
<tr>
<td>f8</td>
<td>20</td>
<td>173</td>
<td>61.1</td>
<td>1.73</td>
<td>282</td>
<td>20.4</td>
<td>224.5</td>
<td>45.1</td>
<td>8.4</td>
<td>720</td>
</tr>
<tr>
<td>f9</td>
<td>21</td>
<td>167</td>
<td>65.0</td>
<td>1.73</td>
<td>266</td>
<td>20.8</td>
<td>320.9</td>
<td>46</td>
<td>8.6</td>
<td>752</td>
</tr>
<tr>
<td>m1</td>
<td>20</td>
<td>176</td>
<td>74.9</td>
<td>1.91</td>
<td>255</td>
<td>7.3</td>
<td>181.0</td>
<td>54</td>
<td>10.3</td>
<td>941</td>
</tr>
<tr>
<td>m2</td>
<td>22</td>
<td>186</td>
<td>71.9</td>
<td>1.95</td>
<td>271</td>
<td>8.2</td>
<td>196.5</td>
<td>63</td>
<td>12.2</td>
<td>1098</td>
</tr>
<tr>
<td>m3</td>
<td>21</td>
<td>181</td>
<td>76.7</td>
<td>1.96</td>
<td>256</td>
<td>9.6</td>
<td>220.7</td>
<td>48</td>
<td>9.1</td>
<td>850</td>
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<tr>
<td>m4</td>
<td>25</td>
<td>181</td>
<td>78.6</td>
<td>1.99</td>
<td>253</td>
<td>7.9</td>
<td>177.4</td>
<td>53</td>
<td>10.0</td>
<td>939</td>
</tr>
<tr>
<td>m5</td>
<td>20</td>
<td>181</td>
<td>82.3</td>
<td>2.03</td>
<td>246</td>
<td>7.0</td>
<td>183.3</td>
<td>54</td>
<td>10.3</td>
<td>992</td>
</tr>
<tr>
<td>m6</td>
<td>19</td>
<td>176</td>
<td>84.4</td>
<td>2.01</td>
<td>238</td>
<td>8.8</td>
<td>223.6</td>
<td>56</td>
<td>10.7</td>
<td>1047</td>
</tr>
<tr>
<td>m7</td>
<td>19</td>
<td>186</td>
<td>83.0</td>
<td>2.08</td>
<td>250</td>
<td>14.1</td>
<td>324.1</td>
<td>51</td>
<td>9.7</td>
<td>939</td>
</tr>
<tr>
<td>m8</td>
<td>25</td>
<td>183</td>
<td>80.8</td>
<td>2.03</td>
<td>251</td>
<td>10.8</td>
<td>231.1</td>
<td>52</td>
<td>9.9</td>
<td>944</td>
</tr>
<tr>
<td>m9</td>
<td>23</td>
<td>183</td>
<td>83.0</td>
<td>2.05</td>
<td>247</td>
<td>12.1</td>
<td>257.6</td>
<td>52</td>
<td>9.8</td>
<td>949</td>
</tr>
</tbody>
</table>

Females 20.7 ± 1.4  171 ± 3  66.6 ± 5.0  1.78 ± 0.07  267 ± 11  21.6 ± 2.8  285.3 ± 37.5  50.3 ± 5.3  9.5 ± 1.1  827 ± 95

Males 21.6 ± 2.4  182 ± 3**  79.5 ± 4.3**  2.00 ± 0.05**  252 ± 9**  9.5 ± 2.4**  221.7 ± 46.9**  53.7 ± 4.1  10.2 ± 0.9  967 ± 72**

Overall 21.1 ± 1.9  177 ± 6  73.0 ± 8.1  1.89 ± 0.13  260 ± 13  15.6 ± 6.7  253.5 ± 52.6  52.0 ± 4.9  9.9 ± 1.0  897 ± 109

\( A_D \) = body surface area; Mass = body mass; \( A_D/M \) = body surface to mass ratio; Predicted VO\(_{2\text{max}}\) = predicted maximal oxygen uptake

Absolute metabolic rate calculated from body mass and running speed (Epstein et al., 1987).

* significantly different from females at p<0.05; ** significantly different from females at p<0.01
Table 3.2. Skinfold thickness (mean ± SD) of the anterior upper body (12 sites), range in brackets

<table>
<thead>
<tr>
<th>Group</th>
<th>forearm</th>
<th>anterior</th>
<th>biceps</th>
<th>shoulder</th>
<th>clavicular</th>
<th>pectoral</th>
<th>chest</th>
<th>nipple</th>
<th>midaxillary</th>
<th>upper abdominal</th>
<th>External oblique</th>
<th>suprailiac</th>
<th>abdominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Females</td>
<td>7.3 ± 1.7</td>
<td>6.9 ± 1.9</td>
<td>7.8 ± 1.8</td>
<td>7.6 ± 1.5</td>
<td>8.6 ± 1.9</td>
<td>11.8 ± 2.2</td>
<td>8.7 ± 1.3</td>
<td>10.8 ± 2.4</td>
<td>13.1 ± 4.3</td>
<td>11.9 ± 3.2</td>
<td>18.7 ± 3.5</td>
<td>13.7 ± 1.0</td>
<td></td>
</tr>
<tr>
<td>Males</td>
<td>5.4 ± 1.0*</td>
<td>4.9 ± 1.5*</td>
<td>6.6 ± 1.6*</td>
<td>4.9 ± 0.8**</td>
<td>7.7 ± 1.8</td>
<td>6.1 ± 1.0**</td>
<td>8.5 ± 2.1</td>
<td>7.7 ± 1.2**</td>
<td>13.6 ± 5.6</td>
<td>10.0 ± 4.2</td>
<td>13.7 ± 5.9*</td>
<td>14.8 ± 4.1</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>6.4 ± 1.6</td>
<td>5.9 ± 2.0</td>
<td>7.2 ± 1.8</td>
<td>6.3 ± 1.8</td>
<td>8.2 ± 1.8</td>
<td>8.9 ± 3.4</td>
<td>8.6 ± 1.7</td>
<td>9.3 ± 2.4</td>
<td>13.3 ± 4.8</td>
<td>11.0 ± 3.8</td>
<td>16.2 ± 5.4</td>
<td>14.2 ± 3.0</td>
<td></td>
</tr>
</tbody>
</table>

* significantly different from females at p<0.05; ** significantly different from females at p<0.01

Table 3.3. Skinfold thickness (mean ± SD) of the lower body (3 sites), posterior upper body (9 sites) and total skinfold thickness, range in brackets

<table>
<thead>
<tr>
<th>Group</th>
<th>thigh</th>
<th>Supra patellar</th>
<th>calf</th>
<th>forearm posterior</th>
<th>triceps</th>
<th>neck</th>
<th>Supra scapular</th>
<th>scapular</th>
<th>Sub scapular</th>
<th>Infra scapular</th>
<th>lumbar</th>
<th>Lumbo sacral</th>
<th>Total Skinfolds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Females</td>
<td>24.3 ± 6.5</td>
<td>7.2 ± 2.5</td>
<td>12.1 ± 2.0</td>
<td>6.2 ± 1.5</td>
<td>16.6 ± 3.4</td>
<td>14.3 ± 2.3</td>
<td>10.5 ± 1.8</td>
<td>11.6 ± 1.9</td>
<td>12.6 ± 2.9</td>
<td>12.9 ± 3.1</td>
<td>19.7 ± 7.5</td>
<td>18.6 ± 5.8</td>
<td>293.6 ± 45.5</td>
</tr>
<tr>
<td>Males</td>
<td>12.9 ± 4.5**</td>
<td>6.2 ± 1.0</td>
<td>10.0 ± 3.8</td>
<td>4.5 ± 0.7**</td>
<td>7.5 ± 1.7**</td>
<td>9.9 ± 1.3**</td>
<td>9.9 ± 2.0</td>
<td>11.5 ± 2.9</td>
<td>10.0 ± 1.4*</td>
<td>10.6 ± 1.6</td>
<td>13.6 ± 4.5</td>
<td>11.1 ± 2.4**</td>
<td>221.7 ± 46.9**</td>
</tr>
<tr>
<td>Total</td>
<td>18.6 ± 8.0</td>
<td>6.7 ± 1.9</td>
<td>11.1 ± 3.1</td>
<td>5.4 ± 1.4</td>
<td>12.0 ± 5.3</td>
<td>12.1 ± 2.9</td>
<td>10.2 ± 1.9</td>
<td>11.5 ± 2.4</td>
<td>11.3 ± 2.6</td>
<td>11.8 ± 2.6</td>
<td>16.7 ± 6.8</td>
<td>14.9 ± 5.6</td>
<td>257.6 ± 58.1</td>
</tr>
</tbody>
</table>

* significantly different from females at p<0.05; ** significantly different from females at p<0.01
3.3.3. Evolution of body temperatures

The evolution of $T_{re}$ revealed a similar pattern between males and females as shown in Figure 3.2. There was no main effect of SEX (p=0.56) but the influence of TIME was significant throughout the protocol (p<0.05). A tendency for a TIME*SEX interaction was found (p=0.056) which can be observed with a larger and faster post exercise drop ($♀ -0.7°C$ vs $♂ -0.5°C$). The effect of SEX was significant for $\bar{T}_{sk}$ (p<0.01) as well as TIME (p<0.01), with no interaction TIME*SEX (p=0.38).

![Figure 3.2](image)

Figure 3.2: Evolution of rectal temperature ($T_{re}$, °C) and mean skin temperature ($\bar{T}_{sk}$, °C) for females ($▲$) and males ($■$) during the experimental protocol. Significantly different from females at * p<0.05 ** p<0.01.

Gross sweat loss did not differ between males and females although being 15% higher for males on absolute terms and showing a much larger inter-individual variability for females ($♀: 185 \pm 133g$ vs $♂: 212 \pm 39g$, p>0.05).

HR, running speeds and RPE at RUN40 were also similar ($♀: 149\pm13bpm$ vs $♂: 151\pm7bpm$; $9.5\pm1.1 \text{ m.s}^{-1}$ vs $10.2\pm0.9\text{ m.s}^{-1}$, $13 \pm 2$ vs $13 \pm 1$, all NS).
3.3.4. Relationships between whole-body parameters

3.3.4.1. Mean skin temperature and overall body fat

Regression analysis was performed on the groups of males and females separately as well as using all the data from both groups combined. Significant correlations were consistently found solely when all data were considered between $T_{sk}$ and %BF and a tendency was observed between $T_{sk}$ and sum of skinfolds (Table 3.4).

Table 3.4. Table of correlation coefficients ($r$ values) for the relationship between $T_{sk}$ and %BF as well as $T_{sk}$ and total sum of skinfolds (24 body sites) for the group of females (♀) and males (♂) (n=9) and for all individuals combined (n=18). □ significant at p<0.05. □ 0.05 < p < 0.1

<table>
<thead>
<tr>
<th>%BF</th>
<th>$T_{sk}$ at PRE</th>
<th>$T_{sk}$ at RUN10</th>
<th>$T_{sk}$ at RUN40</th>
<th>$T_{sk}$ at POST10</th>
</tr>
</thead>
<tbody>
<tr>
<td>♀</td>
<td>0.62B</td>
<td>0.26</td>
<td>-0.18</td>
<td>-0.33</td>
</tr>
<tr>
<td>♂</td>
<td>-0.11</td>
<td>-0.01</td>
<td>-0.37</td>
<td>-0.14</td>
</tr>
<tr>
<td>ALL</td>
<td>-0.67</td>
<td>-0.60</td>
<td>-0.58</td>
<td>-0.55</td>
</tr>
<tr>
<td>sum of skinfolds</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>♀</td>
<td>0.16</td>
<td>-0.11</td>
<td>-0.06</td>
<td>-0.14</td>
</tr>
<tr>
<td>♂</td>
<td>0.01</td>
<td>0.06</td>
<td>-0.29</td>
<td>0.01</td>
</tr>
<tr>
<td>ALL</td>
<td>-0.45</td>
<td>-0.44</td>
<td>-0.46</td>
<td>-0.36</td>
</tr>
</tbody>
</table>

The variability between subjects is highlighted in Figure 3.3 showing the relationships at a specific stage. There is more overlap between individual data point when total sum of skinfolds is considered.

![Figure 3.3](image-url)

**Figure 3.3.** Mean skin temperature $T_{sk}$ (°C) in relation to body fat percentage (%BF) and total sum of skinfolds (mm) for males (■), females (▲) at stage RUN40. significant at * p<0.05, □ 0.05 < p < 0.1
3.3.4.2. Mean skin temperature and metabolic rate

The relationship between $T_{sk}$ and absolute metabolic rate is presented in Figure 3.4.

![Mean skin temperature $T_{sk}$ (°C) in relation to metabolic rate (W) for males (■) and females (▲) and both groups combined (---) at stage RUN40. significant at * p<0.05, ** p < 0.01](image)

**Figure 3.4.** Mean skin temperature $T_{sk}$ (°C) in relation to metabolic rate (W) for males (■) and females (▲) and both groups combined (---) at stage RUN40. significant at * p<0.05, ** p < 0.01

3.3.4.3. Mean skin temperature and overall subjective votes

There was no significant correlation between $T_{sk}$ and overall subjective votes (TS and TC), considering each group separately or all data combined, throughout the whole protocol. A tendency was yet shown for the male group at RUN40 between overall TS and $T_{sk}$ ($r = 0.65, p=0.08$).

3.3.5. Patterns of skin temperature distribution

The following figures (Figure 3.5-3.8) provide quantitative data about the topography of $T_{sk}$ over a reference male and female body shape. Each pixel of the absolute body map corresponds to the arithmetic average (pixel by pixel in the matrix) of the morphed individual thermograms at each specific stage. The relative maps allow for a valid comparison between sexes in terms of similarities or differences of the patterns as they are taken into account $T_{sk}$. Bras were worn for females during the protocol but removed for infrared measurements. Hands are deliberately not shown because of the limited number of pixels on the fingers which questions the accuracy of the measurement (edge related issues). Moreover,
morphing was not very successful in this region and resulted in misalignment errors once averaging individual thermograms.

Figure 3.5. Averaged maps of absolute (left panel) and relative (right panel) skin temperature patterns before exercise (PRE) for females (♀) and males (♂) after morphing individual images of the 9 participants in each group to a reference body shape. Relative maps are obtained by dividing the original absolute map by the $\bar{T}_{sk}$ of the group at the specific stage. A value of 1 corresponds to the group mean $\bar{T}_{sk}$. 
Figure 3.6: Averaged maps of absolute (left panel) and relative (right panel) $T_{sk}$ patterns after 10 minutes of running at $\dot{V}O_{2,max}$ (RUN10) for females (♀) and males (♂) after morphing individual images of the 9 participants in each group to a reference body shape. Relative maps are obtained by dividing the original absolute map by the $\bar{T}_{sk}$ of the group at the specific stage. A value of 1 corresponds to the group- $\bar{T}_{sk}$. 

Figure 3.7. Averaged maps of absolute (left panel) and relative (right panel) $T_{sk}$ patterns after 40 minutes of running at $\dot{V}O_{2,max}$ (RUN40) for females (♀) and males (♂) after morphing individual images of the 9 participants in each group to a reference body shape. Relative maps are obtained by dividing the original absolute map by the $T_{sk}$ of the group at the specific stage. A value of 1 corresponds to the group-$T_{sk}$. 
Figure 3.8. Averaged maps of absolute (left panel) and relative (right panel) skin temperature patterns after 10 minutes of post-exercise passive (POST) for females (♀) and males (♂) after morphing individual images of the 9 participants in each group to a reference body shape. Relative maps are obtained by dividing the original absolute map by the $T_{sk}$ of the group at the specific stage. A value of 1 corresponds to the group-$T_{sk}$. 
Table 3.5. Significance levels of comparisons for ABSOLUTE and RELATIVE skin temperature between males and females at all stages of the protocol (PRE, RUN10, RUN40, POST) for both uncorrected differences and Holm-Bonferroni corrected differences (at p<0.05). Represents a significant difference (p<0.05) and the value corresponds to the subtraction (males - females, in °C).

<table>
<thead>
<tr>
<th>Anterior Body</th>
<th>POSTERIOR BODY</th>
<th>LATERAL BODY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRE</td>
<td>28.2</td>
<td>28.1</td>
</tr>
<tr>
<td>RUN10</td>
<td>26.1</td>
<td>26.2</td>
</tr>
<tr>
<td>RUN40</td>
<td>26.3</td>
<td>26.1</td>
</tr>
<tr>
<td>POST</td>
<td>28.3</td>
<td>28.2</td>
</tr>
</tbody>
</table>

Table 3.6. Minimum, maximum skin temperature (°C) for the anterior, posterior and lateral body with corresponding region names and number for the group of males and females at the four protocol stages. Group-average of the max-min difference (°C) and group-average standard deviation of skin temperature over the whole body.

<table>
<thead>
<tr>
<th>Anterior Body</th>
<th>Posterior Body</th>
<th>Lateral Body</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIN (° C)</td>
<td>MAX (° C)</td>
<td>MIN (° C)</td>
<td>MAX (° C)</td>
</tr>
<tr>
<td>PRE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>22.9</td>
<td>29.6</td>
<td>25.8</td>
</tr>
<tr>
<td>F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RUN10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>20.0</td>
<td>26.0</td>
<td>21.6</td>
</tr>
<tr>
<td>F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RUN40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>22.4</td>
<td>27.8</td>
<td>23.2</td>
</tr>
<tr>
<td>F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POST</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>22.4</td>
<td>27.8</td>
<td>23.2</td>
</tr>
<tr>
<td>F</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Lateral body regions:
- 30 Low Abdomen
- 31 Upper Abdomen
- 32 Chest
- 33 Arm Pit
- 34 Scapular
- 35 Cheek

88
Figure 3.9 and 3.10 display the maps of the $T_{sk}$ standard deviation (SD) from the series of morphed individual thermograms (SD pixel by pixel). It represents the variability of thermal patterns between subjects. The head region is sometimes missing in the posterior view due to morphing misalignments producing a very high deviation exceeding the range of the scale.

Figure 3.9. Morphed maps of skin temperature standard deviation for males ($♂$) and females ($♀$) on the reference body shape at PRE and RUN10. Upper panels present the posterior body and lower panels present the anterior body.
From the above figures, no specific patterns can be observed on the different body maps which suggest that the patterns observed in Figures 3.5-3.8 on the absolute and relative body maps are relatively consistent for any individual. The largest variability was found at RUN40 especially for males over the chest region which is a relatively warm region with superficial vascularisation as discussed in 4.4.

3.3.6. Local skin temperature and local skinfold thickness

The association of local $T_{sk}$ and local SFT was performed for 17 body sites. Relationships were analysed for each group separately and for all data combined. Only 22 significant correlations were significant (out of 204 possible). The thigh region was the only site with a consistent significant correlation at every stage considering all individuals. However, no significant relationships were observed within the group of males or females for this region (Table 3.7).
Table 3.7. Correlation coefficient tables (r values) for the relationship between local skin temperature and local skinfold thickness at all protocol stages for the group of females, males and all data combined.

<table>
<thead>
<tr>
<th></th>
<th>Forearm Ant.</th>
<th>Biceps</th>
<th>Shoulder</th>
<th>Pectoral</th>
<th>Clavicular</th>
<th>External Oblique</th>
<th>Upper Abdomen</th>
<th>Suprailiac</th>
<th>Abdomen</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PRE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>♀</td>
<td>-0.27</td>
<td>-0.06</td>
<td>-0.09</td>
<td>-0.20</td>
<td>0.65</td>
<td>-0.33</td>
<td>0.11</td>
<td>0.37</td>
<td>-0.10</td>
</tr>
<tr>
<td>♂</td>
<td>0.56</td>
<td>0.11</td>
<td>-0.36</td>
<td>-0.06</td>
<td>0.08</td>
<td>0.12</td>
<td>0.10</td>
<td>-0.24</td>
<td>-0.21</td>
</tr>
<tr>
<td><strong>ALL</strong></td>
<td>-0.50</td>
<td>-0.44</td>
<td>-0.40</td>
<td>-0.29</td>
<td>-0.20</td>
<td>0.07</td>
<td>0.12</td>
<td>-0.27</td>
<td>-0.04</td>
</tr>
<tr>
<td><strong>RUN10</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>♀</td>
<td>0.27</td>
<td>0.35</td>
<td>0.17</td>
<td>0.13</td>
<td>0.50</td>
<td>0.27</td>
<td>0.10</td>
<td>0.43</td>
<td>-0.11</td>
</tr>
<tr>
<td>♂</td>
<td>0.16</td>
<td>0.06</td>
<td>-0.37</td>
<td>-0.17</td>
<td>0.15</td>
<td>0.20</td>
<td>0.09</td>
<td>-0.39</td>
<td>-0.19</td>
</tr>
<tr>
<td><strong>ALL</strong></td>
<td>-0.18</td>
<td>-0.39</td>
<td>-0.39</td>
<td>0.11</td>
<td>-0.51</td>
<td>0.13</td>
<td>0.09</td>
<td>-0.38</td>
<td>-0.03</td>
</tr>
<tr>
<td><strong>RUN40</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>♀</td>
<td>0.43</td>
<td>0.01</td>
<td>-0.57</td>
<td>-0.31</td>
<td>-0.18</td>
<td>-0.10</td>
<td>-0.03</td>
<td>-0.16</td>
<td>-0.17</td>
</tr>
<tr>
<td>♂</td>
<td>0.13</td>
<td>-0.15</td>
<td>-0.21</td>
<td>0.10</td>
<td>-0.14</td>
<td>-0.23</td>
<td>-0.17</td>
<td>-0.72</td>
<td>-0.57</td>
</tr>
<tr>
<td><strong>ALL</strong></td>
<td>0.13</td>
<td>-0.40</td>
<td>-0.47</td>
<td>-0.09</td>
<td>-0.32</td>
<td>-0.15</td>
<td>-0.12</td>
<td>-0.67</td>
<td>-0.27</td>
</tr>
<tr>
<td><strong>POST</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>♀</td>
<td>0.29</td>
<td>-0.30</td>
<td>-0.58</td>
<td>-0.39</td>
<td>0.08</td>
<td>-0.33</td>
<td>-0.40</td>
<td>-0.09</td>
<td>-0.35</td>
</tr>
<tr>
<td>♂</td>
<td>0.18</td>
<td>0.31</td>
<td>0.39</td>
<td>0.26</td>
<td>0.24</td>
<td>0.30</td>
<td>0.03</td>
<td>-0.19</td>
<td>-0.20</td>
</tr>
<tr>
<td><strong>ALL</strong></td>
<td>0.07</td>
<td>-0.30</td>
<td>-0.27</td>
<td>-0.04</td>
<td>0.09</td>
<td>0.12</td>
<td>-0.17</td>
<td>-0.42</td>
<td>-0.12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Forearm Post.</th>
<th>Forearm Infra scapular</th>
<th>Hip</th>
<th>Thigh</th>
<th>Patella</th>
<th>Calf</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PRE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>♀</td>
<td>-0.07</td>
<td>0.47</td>
<td>0.16</td>
<td>0.42</td>
<td>0.33</td>
<td>0.31</td>
</tr>
<tr>
<td>♂</td>
<td>-0.13</td>
<td>0.48</td>
<td>-0.26</td>
<td>-0.18</td>
<td>0.03</td>
<td>-0.14</td>
</tr>
<tr>
<td><strong>ALL</strong></td>
<td>-0.07</td>
<td>0.47</td>
<td>-0.34</td>
<td>-0.05</td>
<td>-0.12</td>
<td>-0.56</td>
</tr>
<tr>
<td><strong>RUN10</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>♀</td>
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</tr>
<tr>
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<tr>
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</tr>
<tr>
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<td></td>
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<tr>
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<td>-0.01</td>
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</tr>
<tr>
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<td>-0.40</td>
<td>0.31</td>
<td>-0.35</td>
</tr>
<tr>
<td><strong>ALL</strong></td>
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<td>0.27</td>
<td>-0.22</td>
<td>-0.39</td>
<td>0.52</td>
<td>0.71</td>
</tr>
<tr>
<td><strong>POST</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>-0.06</td>
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<td>-0.52</td>
</tr>
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</tr>
<tr>
<td><strong>ALL</strong></td>
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<td>-0.27</td>
<td>0.37</td>
<td>-0.33</td>
<td>0.46</td>
<td>-0.68</td>
</tr>
</tbody>
</table>

The following figures illustrate the relationships for two body sites showing different interindividual variability for the two different groups investigated.

Figure 3.11. Local skin temperature (°C) in relation to local skinfold thickness (mm) for two body locations (scapula and thigh) at PRE and RUN40 for males (■) and females (▲) and both groups combined. (---) * significant at p<0.05
3.3.7. Spatial variations of skin temperature across the body

The distribution of $T_{sk}$ was analysed with the corresponding SFT distribution based on the 17 corresponding locations. Regression analysis was performed between body regions, therefore looking at within-subject variations (intra-individual). We can therefore investigate whether patterns of $T_{sk}$ could be explained by patterns of fat thickness distribution. Across the whole body, there was no significant correlation between local $T_{sk}$ and local SFT when all 17 body regions were taken together, for the group of males, females and both combined.

This was significant considering the anterior torso (6 body regions) for the group of males (at PRE, $r = -0.79$; at RUN10, $r = -0.83$; at RUN40, $r = -0.85$; at POST, $r = -0.79$; p<0.05) for both groups combined (at PRE, $r = -0.74$; at RUN10, $r = -0.79$; at RUN40, $r = -0.79$; at POST, $r = -0.72$, p<0.01). A tendency towards significance was found for the groups of females at all stages.

![Figure 3.12.](image)

Figure 3.12. Average local skin temperature ($^\circ$C) in relation to average skinfold thickness (mm) across the whole body (left) and across the anterior torso (right) at RUN40 for males (■) and females (▲) and both groups combined (---). Significant at * p<0.05 ** p<0.01. The following torso regions were selected in the analysis (#4,7,14,15,17,18 see Fig. 2.8, not #7 because of the bra for females).

3.3.8. Variations of skin temperature within a body region

A similar analysis to 3.2.7 was performed in order to compare the different body regions across the body. This was applied to standard deviation (SD) of $T_{sk}$ at each location, averaged for all individuals. Regression analysis was used between the distribution of local SD and the distribution of SFT. The aim was to observe whether SFT could dictate the variations of $T_{sk}$ at one location (within-subjects).
For males, there was indeed less $T_{sk}$ variations in the vicinity of a skinfold site with large SFT. This was not true for females.

![Figure 3.13. Average local skin temperature variance (°C) in relation to average local skinfold thickness (mm) across the whole body at PRE (left) and RUN40 (right) for males (■) and females (▲). Significant at * p<0.05 ** p<0.01](image)

For males, there were less $T_{sk}$ variations in the vicinity of a body region with large SFT. This was however not true for females.

### 3.3.9. Subjective responses

The subjective responses for overall thermal sensation and comfort are presented as medians for the two populations (Figure 3.14) representing the average person, limiting the influence of extreme responses. The 2-way repeated measures ANOVA revealed no significant effect of SEX or interaction SEX*TIME but a significant influence of TIME on thermal sensation (p<0.01). There was a tendency for warmer overall thermal sensation votes for females compared to males at RUN10 (p=0.09).

![Figure 3.14. Median overall thermal sensation and comfort votes for females (▲) and males (■) at the four different stages of exercise (PRE, RUN10, RUN40, POST) # difference between males and females (0.05< p < 0.1) using individual independent t-tests](image)
No significant effect of SEX was found for local thermal sensation votes in the 11 body regions investigated. Specifically at RUN40 and only few locations, some significant differences were yet observed: females reported warmer dorsal hands (♀: 0 vs ♂: -3, p<0.05). At PRE, the abdomen (♀: -2 vs ♂: 0, p=0.08) and anterior arms (♀: -2 vs ♂: -1, p=0.06) showed a tendency to be perceived colder for females.

No significant effect of SEX was found for local thermal comfort votes in the 11 body regions investigated. Specifically at RUN40, dorsal hands were found to be significantly more comfortable for females (♀: 0 vs ♂: -1, p<0.05). At PRE, a tendency was shown for the face being less comfortable for females (♀: -1 vs ♂: 0, p=0.07).

3.3.10. Local skin temperature and local subjective votes

Over the four stages, there was almost no significant correlation between subjective votes (TS\text{local}, TC\text{local}, TS\text{overall}, TC\text{overall}) and local T\text{ak} as presented in Table 3.8.

| Table 3.8. Correlation coefficient tables (r values) for the relationship between local thermal votes and local skin temperature at different body regions for the group of females (F), the group of males (M) and all individuals combined (ALL) at the four protocol stages (PRE, RUN10, RUN40, POST).

<table>
<thead>
<tr>
<th>Stage</th>
<th>Joint Type</th>
<th>PRE</th>
<th>♂</th>
<th>♀</th>
<th>POST</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TS\text{local}</td>
<td>TF local</td>
<td>TF local</td>
<td>TF local</td>
<td>TF local</td>
</tr>
<tr>
<td></td>
<td>TC\text{local}</td>
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<td>TF local</td>
<td>TF local</td>
<td>TF local</td>
</tr>
<tr>
<td></td>
<td>TS\text{overall}</td>
<td>TF overall</td>
<td>TF overall</td>
<td>TF overall</td>
<td>TF overall</td>
</tr>
<tr>
<td></td>
<td>TC\text{overall}</td>
<td>TF overall</td>
<td>TF overall</td>
<td>TF overall</td>
<td>TF overall</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>OVERALL</th>
<th>CHEST</th>
<th>ABDOMEN</th>
<th>U.BACK</th>
<th>L.BACK</th>
<th>ARMS ant.</th>
<th>ARMS post</th>
<th>LEGS ant.</th>
<th>LEGS post</th>
<th>HANDS back</th>
<th>HANDS palmar</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRE</td>
<td>0.05</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>RUN10</td>
<td>0.05</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>POST</td>
<td>0.05</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**Note:** Significant at p<0.05
TS local: Local thermal sensation, TC local: local thermal comfort
TS overall: overall thermal sensation, TC overall: overall thermal comfort.

Lastly, there was a significant relationship between the distribution of TS\textsubscript{local} and the distribution of local T\textsubscript{sk} solely at the end of exercise (RUN40) as presented in Figure 3.15. This corresponds to a within-subject analysis as opposed to the previous table looking at between-subjects correlation.

![Figure 3.15](image)

Figure 3.15. Average local thermal sensation in relation to average local skin temperature (°C) for females (▲) and males (■) at PRE and RUN40. Each data point represents a single body region.

No correlations were found between the distribution of TC\textsubscript{local} and the distribution of local T\textsubscript{sk} neither for males nor for females.
3.4. Discussion

3.4.1. Distribution of skinfold thickness

The differences in the anatomical position of adipose tissue, also called fat patterning, represents one of the main sexual diphormism between males and females. On a population level, two different body fat distributions have been identified with centralized (android) fat patterning in men and generalized (gynoid) in women (Mueller et al., 1985). Results from this study show skinfold thickness mapping are in line with these two distinct distributions despite the recruitment of relatively young and fit people.

From Table 3.2, the larger skinfold thicknesses for females at the suprailiac (+5mm), lumbar (+6.1mm), lumbosacral (+7.5mm) and thigh (+11.4mm) body sites are the most pronounced differences and reflect the gynoid pattern, i.e subcutaneous fat located in the gluteo-femoral region. Typical areas of fat deposits were also found in women in our measurements such as the triceps (+9.1 mm) and the breast region (+5.7mm). The presence of larger amount of subcutaneous fat, especially in the lower body region could be integrated in an evolutionary prospective as this represents an important energy stores enabling the female body to bear the energetic costs of pregnancy and lactation (Kirchengast and Huber, 2001). The relationships between body fat variables and skin temperature variables are discussed in 3.4.3.

Although not significant, the upper abdominal and abdominal sites were the only ones with an absolute thicker skinfold for the group of males (+0.5mm and +1.1mm respectively) which is in line with the centralized (android) fat topography with accumulation of fat in the abdominal region found in males. The absence of significant differences for these sites can be explained by the narrow range of relatively fit ($\dot{VO}_{2,\text{max}} = 50.3 \text{ mL.min}^{-1} \cdot \text{kg}^{-1}$) and lean (9.5% BF) males recruited for this specific study.

- The subcutaneous fat thickness distribution of relatively fit and lean participants reflected the sexual dimorphism of the general population.
3.4.2. Evolution of body temperatures

Exercise intensity was chosen as a relative workload (%$\dot{V}O_{2,\text{max}}$) in order to mimic the conditions encountered by active runners of both sexes during their training sessions. As there was no significant difference in relative physical fitness, females consequently had a lower absolute metabolic heat production (Havenith, 2001a) as shown in Table 3.2. $T_e$ change is paralleled with change in body heat content until total heat loss matches metabolic heat production (Burse, 1979) which corresponds to a state of equilibrium in the heat balance.

Despite a lower absolute metabolic heat production in females (lower body mass), the differences in heat storage capacity may partly explain the similar change in $T_e$ with the lower specific heat of fat in females, being more than twice more important for them on average ($\varphi$: 21.6% vs $\sigma$: 9.5% BF).

A larger post-exercise drop in $T_e$ was observed in our results. This has also been reported by Marchand et al. (2001) at 24°C and similar conditions (45-min run at 75% $\dot{V}O_{2,\text{max}}$), postulating the role of a larger heat flux from the forearm at the cessation of exercise. Considering the larger skin-to-environment temperature gradient at 10°C in the present study compared to Marchand et al. (2001), the dissipation of heat may have been maximised, especially with the favourable surface area-to-mass ratio of females.

No significant differences were observed when analysing the effect of menstrual cycle phase and time of day on $T_e$ in our results, though the sample size was limited. The interaction of these parameters in the present study and the overall stress of exercise and cold exposure may have overridden slight influences of circadian (Reilly and Brooks, 1986) and hormonal variations (Haymes, 1984; Kolka and Stephenson, 1997).

The absolute difference in $T_{sk}$ between sexes was on average 1.8°C (lower for females) throughout the protocol. Various underlying and combined physiological mechanisms may be involved in this discrepancy.

At rest, Burse et al. (1979) have measured a greater degree of peripheral vasoconstriction for women in a cold environment but this was not found later by Wagner and Horvath (1985). Overall, it is still controversial whether the lower $T_{sk}$
for females can also be attributed to body fat (Wagner and Horvath, 1985; Stevens et al., 1987). There was an overall significant negative correlation between $\bar{T}_{sk}$ and %BF in this study but it was not the case for each group on its own. Moreover, the large distinction between the groups may have artificially skewed the relationship and a more homogenous continuum of participants with varying body fat would be required to elucidate this issue. In similar conditions (2 hours rest at 10°C), Buskirk et al. (1963) combined a group of males and females (from 10.9 to 50.9% BF) and also found a negative correlation between $\bar{T}_{sk}$ and %BF. The same limitation as in our finding prevails as there were only two females and both were obese. All the other studies found negative correlations with groups of males (Baker and Daniels, 1956; Oksa et al., 1993; Snellen et al. 1994).

During exercise, our results are in agreement with the existing literature as women maintained a 1.5°C lower $\bar{T}_{sk}$. However, our protocol was using a relative exercise intensity as opposed to the absolute exercise intensity of the literature (Graham, 1983; Walsh and Graham, 1986). They found an increase in heat production in men at the same absolute workload for both genders which led to a 1-2°C lower $\bar{T}_{sk}$ for females (Graham, 1988). It would be interesting to compare $\bar{T}_{sk}$ between sexes at the same rate of heat production in a cold environment in order to assess the relative role of physical characteristics. During exercise, the metabolic heat production indeed becomes a determining factor for $\bar{T}_{sk}$ as identified by Havenith and van Middendorp (1990) on top of the environmental conditions. Our analysis demonstrated that there was a significant positive relationship between $\bar{T}_{sk}$ and metabolic rate (Figure 3.4), being more pronounced at RUN40 than RUN10, and highlighted for both groups combined and also within groups. Most importantly, stepwise regression revealed metabolic rate to be the only significant factor ($p<0.05$) during exercise but not body fat.

- Anthropometrical characteristics may explain the large post-exercise drop in $T_{re}$ in females. Regarding $\bar{T}_{sk}$, our results obtained by infrared thermography are in agreement with the literature. They are not yet conclusive about the absolute influence of body fat on $\bar{T}_{sk}$ and it appears that absolute metabolic rate may be the determining factor during exercise.
3.4.3. Patterns of skin temperature distribution

The present whole-body maps of $T_{sk}$ distribution during exercise, representing a population rather than just an individual, provide novel information with a strong descriptive potential. Early work from Clark and Edholm (1985) reported whole-body thermograms of many interventions or situations (cold stress, running, pregnancy, etc.) but on individual cases. Several studies have used infrared imaging during exercise, more specifically whilst running (Cena and Clark, 1976; Clark et al., 1977; Veghte et al., 1979; Roberts et al., 2007; Merla et al., 2010) but none combined the individual thermograms in order to give a population average pattern. The following sections describe the similarities and differences highlighted by the absolute and relative body maps of skin temperature (Figures 3.5-3.8). Patterns have been analysed according to the main $T_{sk}$ determinants, the areas of heat production and the regional variations of heat loss (Houdas et al., 1975).

Similarities in female and male skin temperature patterns

Despite the absolute $T_{sk}$ differences between males and females (on average 1.8°C colder for females), it was clear that $T_{sk}$ topography followed similar patterns over the body regardless of the exercise period, as observed on the relative body maps. Several consistent features of the $T_{sk}$ patterns present in both sexes can be highlighted:

- A plain warmer Y-shape region was readily noticeable in the participants’ back. This was present on the female pattern despite the presence of the bra thermal signature. Clark et al. (1977) reported a T-shape for male participants running at 16 km.h$^{-1}$ and exposed to 4.5 m.s$^{-1}$ wind. Individual thermograms of resting adult male and female in a 22°C environment also exhibited this Y-shape region over the back (Clark and Edholm, 1985). This topography is in good accordance with the position of brown adipose tissues (BAT) in babies and recently found in adults, tissues being particularly active in lean adults exposed to cold (Cypess et al., 2007).
Although the thermogenic relevance of BAT for $T_{sk}$ remains to be elucidated, the important vascularisation to perfuse these tissues may explain the Y-shape. Moreover, the internal vertebral venous plexus (along the spine) potentially drains the metabolic heat produced by the leg muscles as found in other mammals (Hoogland et al., 2012).

- A colder Y-shape region of colder $T_{sk}$ was observed over the anterior torso. This was slightly impacted by the thermal signature of the sports bra for females. The pectoral, hypogastric and umbilical regions appeared colder than the hypochondriac regions (flanks) and the sternal region (overlying the aortic arch) with the dense network of blood vessels coming from or returning to the heart. The insulation provided by both the subcutaneous fat and the abdominal (rectus abdominis) and pectoral (pectoralis major) muscles may explain this region of colder $T_{sk}$. Muscles indeed have a large insulative benefit in the cold offering a reduction in core-to-skin conductance when they are not perfused (Rennie, 1988). The combined cold exposure, forced convection and low activity of these muscles during running may have maximised their benefits in terms of insulation. Individual thermograms from other studies also exhibited such colder pectoral and umbilical regions at rest (Veghte, 1965; Hayward et al., 1973; Clark and Edholm, 1985) or after exercise (Hayward et al., 1973; Torii et al., 1992) on individual thermograms.

- Body creases, induced by the specific human morphology or body motions during running, appear warmer than the surrounding tissues. The orbital, supraclavicular and sternal regions (for morphological reasons) as well as the popliteal fossa and the volar elbow (knee and arm flexion during exercise) were consistently the warmest regions for both sexes due to the cross-radiation effect (Barnes, 1963) and the regular contact of skin surfaces.
- The pattern of $T_{sk}$ over the **posterior lower limb** mainly reflects the heat transfer from gastrocnemii and hamstrings muscles. It seems that a specific warmer path corresponds to the superficial small saphenous veins. Other studies have also reported warmer $T_{sk}$ over active muscles whilst running (Clark *et al.*, 1977; Vegthe *et al.*, 1979). Local heat produced within the muscles offset the convective heat loss caused by leg swing and air velocity. For both males and females, the upper lateral thighs always appear colder and it can be assumed that the buttocks are also colder (under the briefs). These regions can be associated with specific fat deposits for both sexes and a deep blood network. The buttocks have been commonly reported to be one of the coldest regions in the body (Veghte, 1965; Clark and Edholm, 1985).

- $T_{sk}$ in the **anterior lower limb** was consistently **warmer** in the tibial region compared to the thigh region, mainly influenced by the heat produced within the calves and the larger skinfold thickness over the thigh region. The patella remained the coldest region for both sexes throughout the protocol.

Lastly, there was no significant sex effect on the $T_{sk}$ variability over the body or the largest temperature difference (Table 3.6). The quantitative comparisons of regional relative $T_{sk}$ values revealed only few significant differences, and mainly before exercise (Table 3.5).

- Qualitative and quantitative evidence has been reported to show the existence of a major similar $T_{sk}$ pattern between males and females despite the absolute $T_{sk}$ difference.

**Differences in female and male skin temperature patterns**

Most of the differences highlighted in the relative body maps could be explained by the presence of the sports bra, with warmer regions surrounding the chest (pectoral, clavicular and upper mid back regions). It even elevated the temperature in the region comprised between the breasts. At this running speed, it was judged not acceptable to perform the exercise without the bra, hence leading to this limitation in the comparison of patterns.

Despite the thermal signature of the bra, other regions also exhibited specific secondary features different than those observed in males. The *hypochondriac* and
epigastric regions remained warmer for females compared to males specifically during resting conditions.

The inner thighs demonstrated the influence of cross-radiation effect in males with the anthropometrically larger quadriceps and even potential conduction (through friction) occurring during running.

More pronounced cooler temperatures were observed at the lower back and hip in females at at the end of exercise and during the post-exercise recovery. These body parts correspond to large fat deposits in females which reflects the gynoid distribution of fat patterning.

- There were only a small number of specific differences between males and females in the $T_{sk}$ patterns, mainly due body geometry and composition.

**Representativeness of the skin temperature patterns**

The inter-individual variability in the $T_{sk}$ topography was assessed with the body maps of $T_{sk}$ standard deviation. No distinct pattern could be observed which suggests that the spatial $T_{sk}$ variations were relatively similar for every individual. Standard deviations (between-subjects) were larger during exercise, which also parallels the larger temperature difference and variability (within-subject) at RUN40 (Table 3.5).

No data in the literature could support or contradict these results insofar as this method has never been employed in the past. However, the consistencies in the patterns between individuals with hot and cold spots have long been speculated (Veghte, 1965; Clark and Edholm, 1985), variability patterns within this study provide some evidence to confirm these hypotheses.

Barnes (1963) and Hunold *et al.* (1992) also indicated the potential reproducibility of infrared thermography stating that duplicate thermal patterns are obtained when repeat thermograms of the same individual are made in the same conditions.

- The major $T_{sk}$ pattern appeared to be consistent between individuals from our groups of lean and active participants.

**Differences between rest and exercise skin temperature patterns**

$T_{sk}$ topography at rest and during exercise was different which is in agreement with Clark *et al.* (1977) obtained on one male runner. They stated that rest and exercise produced completely different $T_{sk}$ distribution through increased muscle metabolism,
changes in skin blood flow and variations in environmental cooling. However, their suggestions were based on absolute thermograms with a limited spatial resolution (AGA Model 680 Thermovision). Our results, with larger resolution and the addition of relative body maps, highlighted more specific exercise-related features. The Y-shape of colder $T_{sk}$ over the front torso became more pronounced during exercise and extended to the deltoid regions. The role of environmental cooling with relative air velocity may be involved in this extensive pattern. The Y-shape of warmer $T_{sk}$ over the posterior became also more pronounced during exercise, which may suggest a specific role of the spine for heat dissipation. The largest sweat rates were also found in this region during running (Havenith et al., 2008a). Warm spots over the lower legs were strongly more pronounced during exercise. Metabolic heat produced within the muscles was conveyed by the blood to the surface (Cooper et al., 1959). This is in line with the important local metabolic activity in the calves during running using Positron Emission Tomography (Fujimoto et al., 1996). Specific well-defined warm spots in the posterior lower legs may well reflect the position of muscle perforators called Dodd’s (medial thigh) Boyd’s (medial leg below knee) and Cockett’s (above ankle) perforators (Ballard and Bergan, 2000 p27). The exercising patterns were identical between RUN10 and RUN40 with larger maximal $T_{sk}$ range at RUN40. The cold regions became colder (e.g abdominal) and the warm regions became warmer (e.g face). Patterns of post-exercise resting conditions were clearly influenced by the exercising pattern. Overall, there was no specific pattern of rewarming as it was relatively homogenous over the whole body. The only slight difference in patterns was observed at the anterior torso with a stronger rewarming of the areas surrounding the Y-shape region and the upper arm. Further investigation could compare the real differences in $T_{sk}$ patterns with cooling observed during rest in the cold and cooling during exercise in the cold. This may highlight a stronger insulative role of subcutaneous fat and superficial muscles as redistribution of blood flow may not be modified during rest (constant vasoconstriction).
Exercise changed the overall \( T_{sk} \) pattern, particularly with an increased contrast between body regions, especially regions with high metabolism such as the lower legs.

### 3.4.4. Local skin temperature and local skinfold thickness

**Analysis at one body region (between-subjects)**

The primary finding was that the occurrence of significant correlations between local \( T_{sk} \) and local SFT was minimal considering the number of body regions (17 sites), the sample size (18 participants in total) and the four stages under investigation. The existence of some relationships could also be questioned because of the large discrepancy in \( T_{sk} \) between the groups of males and females. Within the groups (n = 9), only 5 negative correlations were found (out of 153 possible) between local \( T_{sk} \) and local SFT, and mainly in the lower body regions (thigh, patella, calf).

Using contact sensors in cold to cool environment (at rest), some authors reported a negative correlation between local \( T_{sk} \) and local SFT usually with wider range in participants’ fat content, at the arm and chest (range: 2-18%BF, Baker and Daniels, 1956), at the lower back (range: 14-36%BF; Frim et al., 1990), at the thigh (range: 7-36%BF; Hashigushi et al., 2010). Using infrared thermography, Livingstone et al. (1987) observed significant relationships between regional temperature and skinfold thickness at the abdomen, chest, lower back, and upper back (p<0.01). The wide range of adiposity (7.6 to 46.4% BF) as well as the protocol (1-h exposure at rest in 18°C environment) may explain the discrepancy within the results (7-28%BF during exercise).

The limited role of skinfold thickness in this study may stem from a large inter-individual variability in other \( T_{sk} \) determinants such as the localized vasomotor adjustments of the cutaneous circulation or the regional heat production of the underlying tissues (both not measured). The lack of overlap at some skinfold sites between the two populations prevents clear conclusions from being drawn and the variability within each group was probably too small to highlight strong relationships.
The thigh region was the only body site with a consistent significant negative correlation at each stage. It was the most significant at RUN40 as could be expected from the environmental cooling and body motion associated with a limited bypass of blood through the quadriceps muscle and subcutaneous tissue even during running.

- Local skin temperature was not determined by local skinfold thickness except for the thigh and this can be due to large variability in individual body characteristics combined with variability of the regional heat transport responses induced by exercise between individuals.

**Patterns of skin temperature and fat distribution (within-subject)**

LeBlanc (1954) was the first to report that the variations in fat thickness could explain not only the differences in $T_{sk}$ of different persons but also to a certain extent, the regional variations of skin temperatures observed over the body in any one individual (within-subject). No study has explored this feature statistically despite reporting this assumption (LeBlanc, 1954; Rintamäki et al., 1988; Frim et al., 1990).

An extensive procedure of numerous skinfolds measurements was therefore performed in the present study in order to address this aspect of $T_{sk}$ distribution. No correlation was found between the distribution of $T_{sk}$ and the SFT distribution when all corresponding body sites (front, back, legs) were plotted together as seen in Figure 3.12. However, there was a significant negative relationship when the distribution over the torso was analysed (6 body sites) and this was true for all data combined at each stage (-0.72 $< r <$-0.79; p<0.01), for the male group during exercise and a tendency was shown for females during exercise. This relationship with the torso sites was stronger with important skin cooling (at RUN40) which suggests that strong contrasts are required to underline the quantitative influence of fat thickness in the specific situation of exercise with cutaneous blood redistribution for heat dissipation. In the posterior torso, cooling was less pronounced and the variability of skinfold thickness was also lower.

- In the conditions of this study, the variations of local skin temperature over the body can only be explained by subcutaneous fat thickness for the torso but not for
other parts of the body. This could be explained by much larger convective cooling which enables a more distinct discrimination of the fat pads location. Warm areas on the body maps should be viewed as areas that cool less than others due to a thinner insulation or more pronounced superficial vascularisation.

**Variations of skin temperature within a body region**

The variation of skin temperature within a body region (or standard deviation) is highly crucial for the determination of the best position of contact sensors in order to compute $T_{sk}$ accurately. It has been shown that $T_{sk}$ may vary by up to 8°C within 2.5 cm (Frim et al., 1990). The body maps in this research reinforce this observation and extend it to the whole-body.

Frim et al. (1990) looked at the relationship between standard deviation of $T_{sk}$ at one site and skinfold thickness. They did not find consistent correlations and therefore speculated that the shape and size, rather than the thickness of the fat pads, are the important characteristics causing the variations in temperature within a region at rest. A minimum amount of fat may be sufficient to provide near maximum variation.

Our results also failed to show any significance across the body (within-subject). For the group of males, they however highlighted that the smallest variation in $T_{sk}$ were observed for areas with thick layer of body fat (Figure 3.13). It could be speculated that sex-specific differences exist in the exact shape of the fat pads within a body location but this may also well be the influence of the underlying musculature distribution or subcutaneous blood perfusion.

Measurements in our study were slightly different than those from Frim et al. (1990) as they used 4 thermistors around a central one at each site as opposed to infrared thermography which gives a more realistic standard deviation in skin temperature within the region. Our environmental conditions were more severe than Frim et al. (1990) (10°C vs 18, 23, 28°C) reinforcing $T_{sk}$ differences between regions.

- Skin temperature was less variable over thicker fat pads. This was only true for the male population and consistent across the whole body.

**3.4.5. Subjective responses between males and females**

Hardy and Dubois (1940) were among the first to investigate thermoregulatory responses of men and women exposed to cold conditions. The “comfort zone” for
women was larger than men (♀: 6°C vs ♂: 3°C) at thermal equilibrium. They speculated that the extension of this zone in the cold side could be due to their thicker subcutaneous fat tissues as well as a potential better adaptation of $T_{sk}$ to meet thermal changes of the environment (Hardy and DuBois, 1940). This hypothesis was later challenged by Kenney (1985) assuming that standardization of clothing may negate this difference. To our knowledge, thermal perceptions of males and females during exercise in the cold have yet to be investigated. Our results showed identical overall and local thermal sensation and thermal comfort during the first minutes of cold exposure standing at rest in a semi-nude condition for both sexes. This was also the case at the end of exercise and during post-exercise recovery. Perceptual responses were similar despite the lower absolute $T_{sk}$ and local $T_{sk}$ values for females compared to males.

The main difference noted in our protocol was observed after 10 minutes of running with the colder overall thermal sensation for males (-2 for ♀ vs -5 for ♂). Decrease in $T_{sk}$ and rate of increase in $T_{re}$ were similar for both sexes, which would suggest the importance of a local driving factor, i.e a local sensation of a specific body region having the largest influence on overall perception (Pellerin et al., 2004). Although not significant between sexes, the males who reported the coldest overall thermal sensation also perceived their hands as very cold and uncomfortable. It is still unclear how peripheral messages from local thermoreceptors are processed within the hypothalamus in order to give an overall sensation (Candas, 2005) but there is some evidence that some local body regions are more sensitive to an absolute stimulation (static) or a thermal change (dynamic) (Cotter and Taylor, 2005). The partial protection of the body core region by the sports bra may also explain the warmer overall sensation for females after the first minutes of exercise.

At RUN40, males perceived their dorsal surfaces of hands colder (♀: 0 vs ♂:-3) and less comfortable (♀: 0 vs ♂:-1) but this had no effect on overall sensation or comfort. It could be hypothesized that runners would prefer a slightly cool sensation whilst reaching peak values in $T_{core}$ at the end of the 40-min running exercise.

Unlike some conclusions of the literature looking at resting thermal comfort, our results during exercise indicated that overall comfort did not necessarily follow the local worst comfort votes as suggested by others (Rugh et al., 2003; Yao et al.,
Thermal perceptions were characterized by large inter-individual variability, mostly related to uncontrolled personal parameters such as the past cultural and climatic experiences associated with expectations of the thermal environment (Auliciems, 1981).

Our bodymapping approach was also offering a novel way to explore the differences between regional thermal votes across the body. A within-subject analysis highlighted that the distribution of regional thermal sensation was positively correlated with the distribution of local $T_{sk}$ during exercise for both sexes. This original finding suggests that exercising participants are able to discriminate between warm and cold regions, but only when $T_{sk}$ contrasts are strong such as observed in our conditions (intense exercise at 10°C in a semi-nude condition).

- The colder thermal sensation for males after 10 minutes of running was the only major difference found during the protocol. The large majority of local sensations and discomforts were similar between genders despite the lower $\overline{T}_{sk}$ and local $T_{sk}$ values for females. A larger sample size would be required to show stronger differences or similarities in subjective responses.
3.5. CONCLUSIONS

The present study aimed at exploring the patterns of skin temperature distribution at different stages of exercise and exploring the relative contribution of subcutaneous fat thickness to these patterns for both males and females. The following conclusions may be drawn:

- Body fat content was not able to explain $\bar{T}_{sk}$ measured by infrared thermography within the groups of lean active males and females. The relationship was significant for both groups combined, though the absence of a body fat continuum questions the validity of the relationship. During exercise at the same relative workload, the absolute metabolic rate was the determining factor for $\bar{T}_{sk}$.

- The bodymapping imaging approach provided evidence of the existence of a major similar $T_{sk}$ pattern between our group of males and females which is also consistent between individuals. Furthermore, the main features of this pattern can be found at rest and during exercise despite the absolute $T_{sk}$ differences found in the different conditions.

- Local $T_{sk}$ was not determined by local SFT except for the thigh and this can be due to large variability in individual body characteristics combined with variability of the regional heat transport responses induced by exercise between individuals.

- The variations of SFT contribute to a small extent to the variations of local $T_{sk}$ over the body. Patterns of $T_{sk}$ are explained by fat distribution only for the anterior torso but not for other parts of the body.

- $T_{sk}$ was less variable over thicker fat pads. This was only true for the male population and consistent across the whole body.
CHAPTER 4

Skin temperature responses of semi-nude males with a large body fat range during inactive and active cold exposure

Chapter Summary

This study was focused on skin temperature variations in 20 males with a continuum from low to high body fat percentage (7-40%BF), split in three groups (LF = 5-10%BF, MF = 10-15%BF, HF = 15+%BF). In a 10°C environment, participants were required to sit for 60 minutes followed by 30 minutes of cycling at 100W. Infrared measurements revealed consistent features (colder V-shape over torso) between the three groups despite absolute skin temperature differences. Mean and regional skin temperature were inversely correlated with %BF and regional skinfold thickness respectively. Rewarming due to exercise was mainly observed in the active legs for LF and MF, and in the hands for HF group. Perceptual responses were similar for all participants regardless of their body fat content. Thanks to the body-mapping approach, a single spot of the pectoral was proposed for the determination of mean skin temperature in semi-nude cold exposure.

Context

Following the results of the previous study on lean exercising males and females, it was judged relevant to further investigate the local and overall influence of skinfold thickness (SFT) on $T_{sk}$ responses. The absence of a continuum in body fat between the two sex groups in the previous study prevented clear conclusions to be drawn. Moreover, the potential large variation in blood flow distribution induced by exercise may have differently affected the thermal insulation provided by skin, muscle and body fat tissues, consequently modifying the thermal patterns over the body. Another study was then designed to overcome these limitations, firstly by the recruitment of participants with a larger body fat range within the same sex group, and secondly by a specific protocol with a long resting cold exposure followed by exercise, clearly
separating phases of low and high heat production leading to different blood flow distribution.
Our main purpose was therefore to investigate the passive and active internal determinants (body fat, vasomotor and metabolic adjustments) dynamically throughout the protocol.

4.1. Introduction
As highlighted by Buskirk et al. (1963), early work investigating cold-air exposure mainly involved military fit subjects and there was a need to understand the thermal responses of different types of populations, specifically with different amounts of body fat. Body composition and particularly the amount of body fat play a protective role to limit the extent of body cooling. This has been shown during cold air exposure with minimal peripheral blood flow (Daniels and Baker, 1961) though most of the reports were based on cold water immersion (Keatinge, 1960; Kollias et al., 1974). In obese people, the large insulation provided by body fat and the typically smaller $A_{Dm}/M$ ratio (surface area-to-mass ratio) compared to lean people are both favourable in reducing heat loss and therefore protect the body core (Anderson, 1999). Superficial layers of muscle have also been suggested to be critical insulators together with subcutaneous fat when blood perfusion is limited (Veicsteinas et al., 1982, Rennie, 1988).

As indicated in Chapter 3, it has been suggested that variations in fat thickness can explain to a certain extent the regional $T_{sk}$ variations observed over the body (LeBlanc, 1954). To our knowledge and apart from the study in Chapter 3, this feature has only been investigated in a limited number of body sites, and only one study described a thermographic analysis isolating the torso region.

Livingstone et al. (1987) indeed used infrared thermography to understand the effect of body composition on $T_{sk}$, looking at the relationship between local SFT and local $T_{sk}$ (absolute and standard deviation) for four large regions (abdomen, chest, upper back, lower back). They highlighted a large point-to-point variation in $T_{sk}$ over small regions but only looked at large regional data for both body fat and $T_{sk}$, not taking into account intra-regional variations. These variations were more pronounced at the lowest air temperature tested (18°C) of the 60-min resting protocol in a minimally clothed condition.
Overall, the $T_{sk}$ distribution will be dependent upon individual characteristics in terms of regional heat production, regional tissue composition, regional blood flow, regional sweat evaporation and regional geometry (Houdas et al., 1975). Amongst all $T_{sk}$ determinants, skin blood flow appears to play a very important role. Skin blood flow and $T_{sk}$ are positively correlated in the extremities (Tanaka, 2003). The architecture of the blood vessels network as well as the depth of the veins and arteries can affect the $T_{sk}$ variations over the body (Hunold, 1992). Heat produced in the vicinity of the muscle is directly transferred to the skin by conduction and also conveyed radially and longitudinally through the cutaneous blood circulation. A cycling exercise was chosen for the present study (as opposed to running) with a well defined muscle recruitment so that a specific $T_{sk}$ distribution could be observed on the active muscles. Furthermore, an increase in metabolic heat production may arise from an increase in skeletal muscle tone referred to as “pre-shivering” (Wagner and Horvath, 1985) and this can lead to shivering thermogenesis later in cold exposure.

Studies in water have demonstrated an inverse relationship between the percentage body fat and the metabolic response for a given decrease in $T_{sk}$ and $T_{core}$ (Tikuisis et al., 1988).

Regarding subjective responses for resting males in cold air, Budd et al. (1991) reported a tendency towards warmer thermal sensation for fatter subjects (range = 15-36%BF) with no change in thermal discomfort, in line with results by Buskirk et al. (1963) (range = 13-51%BF). On the other hand, Baker and Daniels (1956) reported that fatter males expressed less discomfort than thinner men (range = 1-18%BF). This could also be further investigated especially by adding local perceptive evaluation in several body regions. Studies at rest have demonstrated that the overall perception was directly associated to the two worst local votes (Zhang et al., 2010). The genesis of thermal perception during exercise may however be slightly different due to a reduced attention to thermal stimuli (McIntyre, 1980).

Our purpose was to extend the fundamental knowledge obtained by Livingstone et al. (1987) using similar type of participants (7-46%BF) and methodology, yet increasing the resolution of the regional investigation (therefore the number of regions) inducing more intense body cooling ($T_a = 10^\circ C$) expected to lead to larger inter and intra-regional $T_{sk}$ differences.
The present study was designed to explore the body fat effect on the $T_{sk}$ distribution patterns during cold exposure in a controlled setting. It was hypothesized that:

1. An inverse relationship will exist between $T_{sk}$ and body fat parameters after cooling
2. $T_{sk}$ pattern will reflect the subcutaneous fat thickness pattern with similar patterns across the population
3. Overall sensation and comfort votes will follow the worst local votes at rest but not during exercise. The regional $T_{sk}$ variations will explain the variations of thermal sensation votes.
4. Increases in blood flow induced by exercise will modify the thermal body map with local correlation between cutaneous blood flow and $T_{sk}$.

4.2. Methods

A large range of participants with varying levels of body fat (7-40%) was obtained to explore the effect of body fat on the dynamics of the skin thermal patterns and other thermoregulatory responses during cold exposure (10°C) at two levels of metabolic heat production. The relationship between $T_{sk}$ and body fat was investigated by looking at the link between local skin temperature ($T_{sk,local}$) and local skinfold thickness ($SFT_{local}$) as well as the relationship between mean skin temperature ($\bar{T}_{sk}$) and overall body fat content (%BF) on one hand and total sum of skinfolds on the other hand. Vasomotor adjustments imposed by the exposure (rest and exercise) were explored with laser Doppler flowmetry in two different circulatory territories (acral and non acral regions). All participants completed a pre-test session and an experimental session on a different day.

4.2.1. Participants

Twenty males were recruited among the student population and staff of Loughborough University. They all signed an informed consent after explanation of the study methods and goals. The following inclusion criteria were used:

- Caucasian participants
- Age 18-30 years old
- Able to perform 30 minutes of moderate exercise
- No current injuries/medications
- Non cold-acclimatized
4.2.2. Pre-Test session
The pre-test session involved anthropometric measurements of height and body mass. Extensive skinfold thickness measurements using a Harpenden caliper were also performed at 24 locations across the right side of the body. Standard locations as well as additional locations in line with Edwards (1950) were used. The large amount of sites gave a finer representation of the distribution of fat thickness that can be associated with corresponding segmented areas of $T_{sk,local}$. Body density was calculated from 7 measurements of skinfold thickness (Jackson and Pollock, 1978) and then converted into % body fat using Siri’s equation (1956).

The second part of the pre-test session consisted of a sub-maximal fitness test following the guidelines of ACSM (2006) using a cycling ramp test with 4 increments of 25 watts starting at 75W. Maximal oxygen uptake was then predicted using ACSM’s equation (2004) and the linearity in the heart rate vs $\dot{VO}_2$ relationship.

Participants were familiarised with the subjective scales (thermal sensation, thermal comfort, RPE) during the first stages of the submaximal test. Scales corresponded to the one used for the generic skin temperature mapping protocol (see Chapter 2.4).

4.2.3. Methodology
The experimental protocol was split into a resting phase (60 minutes) and an exercising phase (30 minutes) in the same cold ambient conditions, similar to the chronology by Hong and Nadel (1979). During the resting phase, the participant sat on an adjustable stool (knees at 90°C, feet flat touching the ground) with no back rest and arms away from the body, the hands resting on two wooden stools. Participants wore standardised swimming trunks, and their personal socks and shoes for the whole protocol. They were asked to keep a straight posture whilst sitting with no behavioural adjustment. They exercised on a cycle ergometer (Monark, Ergomedic, Sweden), at a fixed 100W power output (50 rpm, digital display and metronome ticks), with the saddle adjusted to their limb length. Figure 4.1 illustrates the whole setting in the climatic chamber. Participants remained in a preparation room (22°C; 40%) before the cold exposure for 15 minutes and returned to it at the end of the exposure.
Six different sets of infrared measurements (using the skin temperature mapping procedure cf Chapter 2) were taken with the Thermacam B2 camera (FLIR Systems Ltd, West Malling, Kent, UK, resolution 160*120pixels, accuracy ± 2°C, thermal sensitivity ± 0.1°C) : before at 22°C, 40% relative humidity (PRE), immediately after entering the climatic chamber at 10°C, 50% rh (0), after 15 minutes of sitting (15), after 60 minutes of sitting (60), after 30 minutes of cycling at 100W (90) and during recovery outside the chamber at 22°C room temperature (POST).

Preceding the infrared measurements, metabolic rate was determined by indirect calorimetry using the Douglas bag method over a 2-min period at rest and 1-min at the end of exercise (90). Gas analysis was performed using a Servomex 1440 system (Crowborough, UK) and the volume of expired gas was measured with a Harvard volume meter.

All experiments were conducted in a climatic controlled chamber (10°C, 50% rh) with minimal air movement (<0.2 m.s⁻¹). Measurements of $T_a$ and $rh$ were taken...
using a Vaisala HMP35DGT sensor (Vaisala, Helsinki, Finland) and recorded at 10 seconds intervals using a data logger (1000 series squirrel Eltek/Grant, Grant Instruments, Cambridge, UK). All participants were exercising at the same absolute workload which was fixed at 100W (50 rpm) so that the intensity and pedalling rate could be sustained for 30 minutes by people with various degrees of aerobic capacity.

Thermal and RPE scales were presented in front of the participants at eye level to facilitate the reading during exercise for the reporting of $T_{S_{local}}$, $T_{C_{local}}$, $T_{S_{overall}}$, $T_{C_{overall}}$.

Heart rate (HR) was monitored using a Polar RS600 monitor (Polar Electro Oy, Kempele, Finland) 5 minutes before each set of infrared measurements. The heart rate belt was worn over a 2-min period and then removed in order to avoid subsequent physiological ($T_s$) and perceptual changes.

Core temperature was monitored throughout the whole protocol using a rectal thermistor (Grant Instruments, Cambridge, UK) and recorded every 1 second using a data logger (1000 series Squirrel Eltek/Grant, Grant Instruments, Cambridge, UK).

Skin blood flow was also monitored continuously via Laser Doppler flowmetry with a MoorLab system (Moor Instruments, Millwey, UK) using a multi-channel probe head (MP1/7-V2), in which laser light is delivered to the skin by a single optic fibre and then sampled from eight optic fibres closely surrounding the source optic. The Laser Doppler probe was attached (using a flexible probe holder and a ring of double-sided adhesive tape) in two different regions of the body: the left index finger tip (similar to Franck et al., 1999) and the inside left forearm, 5cm below the elbow crease (similar to Savourey et al., 1996). The probe was placed within the location and gently taped with 3M adhesive tape by the same experimenter so that no added pressure could interfere with the measurements. Doppler perfusion units were recorded at a 1-s sampling frequency. Thermistor probes (Grant Instruments, UK) were also taped in the vicinity of the Doppler probes (1cm below) and plugged onto a Squirrel data logger (also used for the rectal thermistor) with a 1-s sampling frequency.

Body mass and clothing mass were recorded upon arrival at the laboratory and immediately after the session using an electronic scale (Mettler Toledo kcc150, Mettler Toledo, Leicester, UK). Participants were provided a swimming trunk
(Tribord, Decathlon, Villeneuve d’Ascq, France) and were required to wear their own socks and trainers.

4.2.4. Analysis
All thermograms were processed using the developed MATLAB procedure in order to obtain average body maps at each phase of the protocol as well as quantitative $T_{sk}$ data for predefined regions. Participants were separated into three body fat groups. Body maps were produced separately for these groups in an attempt to provide three representative maps in the body fat continuum. A single average map may indeed be hard to interpret considering the potential large differences in $T_{sk}$ induced by large differences in body fat. Relative body maps were also produced at each protocol stage and they reflected the body map of each group relative to each group’s $T_{sk}$ at each stage. The $T_{sk}$ distribution (thermal pattern) above and below $T_{sk}$ could then be compared between groups.

Oxygen uptake ($\dot{V}O_2$ in L.min$^{-1}$) was converted into metabolic heat production (in W.m$^{-2}$) using ISO8996 based on the energy equivalent per litre of oxygen consumed which is in turn dependent upon the respiratory quotient (RQ) and the body surface area ($A_{Du}$) calculated with the formula from DuBois and DuBois (1916).

$$M = (0.23*RQ+0.77)*5.88 * \dot{V}O_2 * \frac{1}{A_{Du}} \ (\text{in W.m}^2)$$

Blood flow data (in Laser Doppler perfusion units) were analysed as a running average of 1-min epochs. At every 5-min interval, a 1-min average was used as a quantitative measure of cutaneous blood flow similar to the methodology used by Frank et al. (1999). Artifacts of the blood flow signal were removed from known but brief phases involving change in the subject posture (during infrared measurements, transition from rest to exercise, walk in/out the climatic chamber).

Mean skin temperature ($T_{sk}$) was calculated as the average of all the pixels measured on the entire body surface by the 5 different thermograms, except for the covered body parts (groin and feet).

Statistical Analysis was conducted using the Statistical Package for the Social Sciences 16.0 (SPSS Inc, Chicago, IL, USA). A two-way repeated measures ANOVA was used to investigate the main effect of TIME and BODY FAT group.
Dependent variables were $T_{re}$, $\overline{T}_{sk}$ and $T_{sk,local}$. Holm-Bonferroni corrections were applied to allow for multiple comparisons when comparing the different body regions investigated. A Pearson-correlation coefficient was obtained following regression analysis between $T_{sk}$ parameters (local or overall) and body fat parameters or perceptual parameters (local or overall).

4.3. Results

4.3.1. Participants

The participants’ characteristics and aerobic fitness are presented in Table 4.1. In young populations, sum of skinfolds was found to explain most of the variance in core cooling (DeGroot et al., 2006). A very high correlation existed between body fat content and sum of 24 skinfolds ($r = 0.99$, $p<0.01$). Body fat content was therefore chosen as the criterion for the establishment of three different body fat categories (Table 4.1) allowing for comparisons with the relevant literature.
### Table 4.1. Participants’ anthropometric characteristics (mean ± SD and range) and predicted aerobic fitness level for three distinct categories of body fat content

<table>
<thead>
<tr>
<th>Body fat group</th>
<th>N</th>
<th>Body fat content (%)</th>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Mass (kg)</th>
<th>( A_{du}/M ) (cm².kg⁻¹)</th>
<th>Sum of skinfolds (mm)</th>
<th>Predicted ( \dot{V}O_2\text{max} ) (mL.min⁻¹.kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LF</td>
<td>8</td>
<td>7.9 ± 1.1$\dagger$</td>
<td>19.9 ± 3.0(18-27)</td>
<td>178 ±5(172-184)</td>
<td>67.3 ± 8.8$\dagger$ (55.2-82.2)</td>
<td>274 ±16$\dagger$ (261-298)</td>
<td>158 ±22$\dagger$ (133-199)</td>
<td>51.4 ±9.1 (40.3-64.6)</td>
</tr>
<tr>
<td>MF</td>
<td>8</td>
<td>12.6 ± 1.6**$\dagger$</td>
<td>21.5 ± 3.9(18-27)</td>
<td>183 ±8(173-195)</td>
<td>77.5 ± 8.4* (62.4-85.4)</td>
<td>257 ±14* (239-282)</td>
<td>235 ±37** (182-203)</td>
<td>51.6 ±9.6 (35.2-65.4)</td>
</tr>
<tr>
<td>HF</td>
<td>4</td>
<td>27.3 ± 10.0**$\dagger$$\dagger$</td>
<td>21.5 ± 2.9(19-24)</td>
<td>179 ±6(174-188)</td>
<td>90.0 ± 6.8**$\dagger$$\dagger$ (83.3-97.5)</td>
<td>232 ±11**$\dagger$ (216-241)</td>
<td>429 ±128**$\dagger$$\dagger$ (305-598)</td>
<td>44.0 ±8.5 (31.5-50.6)</td>
</tr>
<tr>
<td>Overall</td>
<td>20</td>
<td>13.7 ± 8.4 (6.6-40.2)</td>
<td>20.9 ± 3.3(18-27)</td>
<td>180 ±6(172-195)</td>
<td>75.9 ± 11.6 (67.3-97.5)</td>
<td>259 ±21 (216-298)</td>
<td>243 ±116 (133-598)</td>
<td>50.0 ±9.2 (31.5-65.4)</td>
</tr>
</tbody>
</table>

$\dagger$ significantly different from LF at p<0.05; $\dagger$$\dagger$ significantly different from LF at p<0.01
$\dagger$ significantly different from MF at p<0.05; $\dagger$$\dagger$ significantly different from MF at p<0.01

There were no significant differences between body fat groups for age, height and fitness level. The low sample size in the HF group demonstrated the difficulty to recruit relatively obese males, all the more on a sport-orientated campus, willing to take part in a laboratory protocol. The final body fat range (7-40%BF) was however deemed satisfactory.

#### 4.3.2. Skinfold thickness

The distribution of skinfold thickness (SFT) over the whole-body is presented for the three body fat groups in Figure 4.3.
The main regions of fat deposits were located in the lower part of the upper body (abdominal region) and this was more pronounced for the HF group. The HF group also revealed some specific large deposits in the triceps and thigh regions. Despite the absolute differences in SFT, the overall pattern of fat distribution was relatively similar between the three categories with HF group reflecting the most the topography variations. The largest average SFT differences (max-min) for LF, MF and HF were 10.5, 16.2 and 34.4mm respectively.

4.3.3. Evolution of thermoregulatory parameters

This section introduces the main factors involved in thermoregulatory changes induced by the cold exposure protocol ($T_{re}$, $M$, $\bar{T}_{sk}$ and GSL). Distinct dynamics of $T_{re}$ were observed between the groups as shown in Figure 4.4.
There was no significant overall effect of BODY FAT on $T_r$ but the interaction BODY FAT*TIME effect was significant ($p<0.05$). The resting and exercising phases were then analysed separately. For the resting phase, there was no significant difference for initial $T_r$ (0) between groups with no overall effect of BODY FAT during the phase but a significant interaction TIME*BODY FAT with a significant drop in $T_r$ observed in LF and no change in $T_r$ for MF and HF towards the end of the resting phase (60).

For the exercising phase, the initial $T_r$ (60) was significantly different for LF vs MF ($p<0.05$) with a tendency for LF vs HF ($p=0.15$, reduced power due to the low HF group size). Throughout the whole exercise, there was an overall effect of BODY FAT and TIME*BODY FAT ($p<0.05$) with HF significantly higher than LF. The end $T_r$ was higher for HF compared to both LF and MF. The initial drop in $T_r$ at the start of cycling was significant for both LF and MF (towards 70 and 75 respectively) and $T_r$ reached significantly higher values than pre-exercise for LF and HF and similar for MF.

There were no differences between the body-fat groups for absolute or relative metabolic heat production (M). The TIME effect was significant ($p<0.01$) only due
to the exercise-associated increase in metabolism at 90. The magnitude of change from pre-exposure to the end of resting values was not significant with no influence of body-fat. However, this corresponded to an average increase of 37% for LF, 30% for MF and 17% for HF which can be analysed as marked shivering for some participants especially in LF and MF (largest increase for the leanest participant = 108%) with muscle contractions visibly observed by the experimenters. Metabolic rate (W.m\(^{-2}\)) at the end of the resting exposure (55) was significantly inversely associated with absolute rectal temperature (r = -0.66, p<0.01). There was a significant positive correlation between relative metabolic rate and RPE at the end of exercise (r = 0.64, p<0.01).

\(\bar{T}\) \(_{sk}\) dynamics were significantly different between the three groups (TIME\*BODY FAT, p<0.01) and there was an overall significant effect of BODY FAT with an average difference of 0.8°C for LF vs MF and 1.2°C for MF vs HF over the test as a whole. Values of \(\bar{T}\) \(_{sk}\) were significantly higher for LF compared to HF over the whole test, higher for LF compared to MF except for PRE and 0, and higher for MF compared to HF except for 15 and 60.

**Figure 4.5**: Evolution of mean skin temperature (°C) for Low-Fat group (LF) Mid-Fat group (MF) and High-Fat group (HF). Error bars indicate SD.
Interestingly, $T_{sk}$ significantly declined during cycling for the HF group, increased for LF and remained constant for MF.

Sweat loss did not differ between LF and MF (65.1±23.6 and 72.4±36.1 g.h$^{-1}$) but was significantly lower for both LF and MF compared to HF (132.0±43.8 g.h$^{-1}$).

On top of the above thermoregulatory parameters, the *overall* subjective votes showed no significant differences between body fat groups. Moreover, the dynamics of thermal sensation and comfort (Figure 4.6) demonstrated a good agreement with the evolution of $T_{sk}$ during the rest exposure and it can be speculated that it was more associated with $T_{re}$ during cycling. Before the exercising phase, $TS_{overall}$ and $TC_{overall}$ consistently followed the lowest local thermal votes. This was still the case for $TC_{overall}$ during exercise but not for $TS_{overall}$ as the dorsal hands were perceived colder than the overall thermal sensation (-4 vs -2 respectively).

![Figure 4.6](image_url)

*Figure 4.6.* Median votes for overall thermal sensation (TS) and overall thermal comfort (TC) for the whole group at the different stages of the protocol.

Median sensation and comfort votes showed identical dynamics. A perception of comfort was associated with a neutral thermal sensation or towards slightly warm sensation. Entering the cold climatic chamber (brief transient) and 30 minutes of
exercise (long transient) were sufficient to elicit an average of 5-unit change in median sensation vote.

In summary, overall perceptual responses were similar between the three body fat groups despite differences in overall thermoregulatory responses. At the end of the resting phase, $T_{re}$ was 0.4°C higher for HF and MF compared to LF. At the end of the exercising phase, $T_{re}$ reached 0.5°C higher values than HF and LF. $T_{sk}$ was 0.8°C higher for LF compared to MF and 1.2°C higher for MF compared to HF, these differences were more pronounced at the end of exercise due to the further $T_{sk}$ drop in HF.

### 4.3.4. Relationships between whole-body parameters

#### 4.3.4.1. Mean skin temperature and overall body fat content

A strong and consistent inverse relationship was found between $T_{sk}$ and %BF for the different test stages (from $r = -0.84$ to $r = -0.91$, $p<0.01$) as shown in Figure 4.7. The relationship was very similar using mean skinfold thickness as the independent variable (or total sum of skinfold thickness) with almost identical correlation coefficients (from $r = -0.83$ to $r = -0.93$, $p<0.01$).

![Figure 4.7](image)

*Figure 4.7*: Mean skin temperature (°C) in relation to overall body fat content (%) for the three main stages of the protocol (0, 55, 90min). Regression coefficients are presented.
4.3.5. Mean skin temperature and overall subjective votes
TS_{overall} or TC_{overall} for individual participants were never correlated with $T_{sk}$ at specific stages of the protocol. However, when all votes were combined for the pre-exercise resting stages (0 to 55), a significant correlation was found between TS_{overall} and $T_{sk}$ on one hand ($r = 0.75$, p<0.01) and TC_{overall} and $T_{sk}$ on the other hand ($r = 0.68$, p<0.01). This was not true for the combined stages following exercise (90 and POST 15).

4.3.6. Patterns of skin temperature distribution
The following figures (Figure 8-13) provide quantitative data about the T_{sk} topography in the three different body fat groups. On the absolute T_{sk} maps, they correspond to the arithmetic average of the group of participants (pixel by pixel in the matrix) from their individual morphed thermograms at each specific stage. The relative maps are obtained by dividing the matrix of the group absolute map by the group $T_{sk}$ at each specific stage. This allows for a valid comparison between body fat groups in terms of similarities or differences in the patterns as they are taking into account the changing overall thermal state of the body. Patterns of T_{sk} distribution will be analysed in the discussion section.
Furthermore, the differences between body-fat groups in absolute and relative T_{sk} (relative to each group $T_{sk}$) are presented in Table 4.2 and 4.3 for a total of 34 regions.
Figure 4.8: Averaged maps of absolute (left panel) and relative (right panel) skin temperature distribution before cold exposure at 22°C (PRE) Low-Fat group (LF) Mid-Fat group (MF) and High-Fat group (HF) after morphing individual images of the participants in each group to a reference body shape. Relative = relative to each group mean skin temperature (=1)
Figure 4.9: Averaged maps of absolute (left panel) and relative (right panel) skin temperature distribution immediately after entering the climatic chamber at 10°C (PRE) Low-Fat group (LF) Mid-Fat group (MF) and High-Fat group (HF) after morphing individual images of the participants in each group to a reference body shape. Relative = relative to each group mean skin temperature (=1)
Figure 4.10. Averaged maps of absolute (left panel) and relative (right panel) skin temperature distribution after 15 minutes of seated cold exposure at 10°C (PRE) Low-Fat group (LF) Mid-Fat group (MF) and High-Fat group (HF) after morphing individual images of the participants in each group to a reference body shape. Relative = relative to each group mean skin temperature (=1).
Figure 4.11. Averaged maps of absolute (left panel) and relative (right panel) skin temperature distribution after 55 minutes of seated cold exposure at 10°C (PRE) Low-Fat group (LF) Mid-Fat group (MF) and High-Fat group (HF) after morphing individual images of the participants in each group to a reference body shape. Relative = relative to each group mean skin temperature (=1).
Figure 4.12. Averaged maps of absolute (left panel) and relative (right panel) skin temperature distribution after 30 minutes of cycling at 100W at 10°C (90) Low-Fat group (LF) Mid-Fat group (MF) and High-Fat group (HF) after morphing individual images of the participants in each group to a reference body shape. Relative = relative to each group mean skin temperature (=1).
Figure 4.13. Averaged maps of absolute (left panel) and relative (right panel) skin temperature distribution after 15 minutes of recovery at 22°C (POST) Low-Fat group (LF) Mid-Fat group (MF) and High-Fat group (HF) after morphing individual images of the participants in each group to a reference body shape. Relative = relative to each group mean skin temperature (=1).
Table 4.2: Significance levels of comparisons for absolute skin temperature between the three groups (LF vs MF; LF vs HF; MF vs HF) at all stages of the protocol (PRE, 0, 15, 55, 90, POST). Significant differences at p<0.05 without correction (upper table) and after Holm-Bonferroni correction (lower table). Values indicate the absolute difference (LF-MF, LF-HF, MF-HF). The figure on the right displays the corresponding numbers for each region presented in the table.
Table 4.3: Significance levels of comparisons for relative skin temperature between the three groups (LF vs MF; LF vs HF; MF vs HF) at all stages of the protocol (PRE, 0, 15, 55, 90, POST). Significant differences at p<0.05 without correction (upper table) and after Holm-Bonferroni correction (lower table). Values indicate the direction of the relative difference (LF-MF, LF-HF, MF-HF). The figure on the right displays the corresponding numbers for each region presented in the table.
Although HF had the lowest $T_{sk}$, they also had the lowest variance of $T_{sk}$ across the body (SD) and this was significantly different from MF and LF at 55 and 90 (SD at 55, LF: 2.5; MF: 2.4; HF: 2.1; SD at 90, LF: 2.5; MF: 2.3; HF: 1.9; p<0.05 without correction). In terms of differences between the coldest and warmest body regions, HF also displayed the smallest contrast and this was significant at 90 (max-min, LF: 12.1±1.9°C; MF: 11.9±2.0°C; HF: 8.6±0.6°C, p<0.05 without correction).

**4.3.7. Local skin temperature and local subjective votes**

Figure 4.14 illustrates the clear BODY FAT effect on absolute $T_{sk}$ for large regions and the absence of effect on $T_{S_{local}}$.

Due to the large inter-individual variability and the low sample size in HF, some differences did not appear significant on subjective votes specifically at 90. It is worth noting that the dorsal and palmar hands had yet significantly higher $T_{S_{local}}$ and $T_{C_{local}}$ for HF, followed by LF, and colder sensation for MF. Posterior and anterior arms at 90 were also perceived as significantly more comfortable for LF compared to MF.

Over the whole protocol (at each stage), there was no correlation between local subjective votes ($T_{S_{local}}$ and $T_{C_{local}}$) and $T_{sk,local}$ and no correlation between local subjective votes ($T_{S_{local}}$ and $T_{C_{local}}$) and %BF using a between-subject approach. Despite colder $T_{sk}$, fatter participants had similar thermal sensation and comfort compared to their leaner counterparts.

Overall, it was however clear that local thermal votes ($T_{S_{local}}$ and $T_{C_{local}}$) correlated well with $T_{sk,local}$ when the resting period was isolated (using all data at PRE, 0, 15, 55) and this was true for all regions (with significant correlation coefficients from $r = 0.62$ to $r = 0.83$ for TS and $r = 0.57$ to $r = 0.81$ for TC).
Figure 4.14. Skin temperature ($T_s$) for large body regions and their corresponding thermal sensation (TS) votes at 0, 55 and 90 for Low-Fat group (LF) Mid-Fat group (MF) and High-Fat group (HF).

* significant difference for LF vs MF ($p<0.05$), ^ significant difference for LF vs HF ($p<0.05$), π significant difference for MF vs HF, uncorrected for multiple comparisons.
The distribution of local thermal votes (T_{sk,local} and T_{C,local}) vs the distribution of T_{sk,local} was compared based on 10 corresponding large regions (same as Figure 4.13) and analysed using a within-subject approach, i.e the overall group average of each region for both T_{sk,local} and local votes (T_{S,local} and T_{C,local}) were used. Significant correlation was obtained between the distributions of T_{S,local} vs T_{sk,local} only at 55 (r = 0.75, p<0.05) and a tendency for T_{C,local} vs T_{sk,local} (r = 0.57, p=0.09). This was consistent for each group separately and for every individual. It means that the variations of thermal votes across the body could be explained by the related variations of T_{sk} for each individual. The lower the T_{sk} of a specific region of the body the lower the associated thermal vote. This was only true at the end of the resting cold exposure but not during exercise despite more pronounced variations in T_{sk} between regions (at 90).

Table 4.4 demonstrates the relationships between thermal votes (T_{S,local}, T_{C,local}, T_{S,overall} and T_{C,overall}) and T_{sk,local} for extended periods of the protocol (all periods, rest periods and exercise/post-exercise).

<table>
<thead>
<tr>
<th></th>
<th>OVERALL</th>
<th>CHEST</th>
<th>ABDOMEN</th>
<th>U.BACK</th>
<th>L.BACK</th>
<th>ARMS ant.</th>
<th>ARMS post</th>
<th>LEGS ant.</th>
<th>LEGS post</th>
<th>HANDS palmar</th>
<th>FACE</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_{S,local}</td>
<td>0.53</td>
<td>0.55</td>
<td>0.39</td>
<td>0.48</td>
<td>0.43</td>
<td>0.48</td>
<td>0.54</td>
<td>0.59</td>
<td>0.51</td>
<td>0.64</td>
<td>0.41</td>
</tr>
<tr>
<td>T_{C,local}</td>
<td>0.47</td>
<td>0.52</td>
<td>0.37</td>
<td>0.47</td>
<td>0.44</td>
<td>0.53</td>
<td>0.50</td>
<td>0.57</td>
<td>0.55</td>
<td>0.65</td>
<td>0.43</td>
</tr>
<tr>
<td>T_{S,overall}</td>
<td>0.53</td>
<td>0.56</td>
<td>0.38</td>
<td>0.47</td>
<td>0.41</td>
<td>0.46</td>
<td>0.52</td>
<td>0.64</td>
<td>0.57</td>
<td>0.48</td>
<td>0.58</td>
</tr>
<tr>
<td>T_{C,overall}</td>
<td>0.47</td>
<td>0.50</td>
<td>0.32</td>
<td>0.42</td>
<td>0.36</td>
<td>0.49</td>
<td>0.50</td>
<td>0.56</td>
<td>0.50</td>
<td>0.52</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Overall, the local thermal votes (T_{S,local} and T_{C,local}) that correlated the most with overall thermal sensation (T_{S,overall}) and comfort (T_{C,overall}) were the chest sensation and comfort (r = 0.93, r = 0.89 p<0.01). The lowest prediction was found for the face but this was still significant (r = 0.74, r = 0.66, p<0.05).

Cold T_{S,overall} was usually associated with cold T_{S,local} at the lower back and palmar hands.

The worst T_{C,overall} (uncomfortable at 55) was associated with local discomfort at the back, posterior arms, anterior legs and hands. For all other stages, only moderate discomfort was experienced, local votes were homogeneous around the overall vote.
In summary, the local subjective votes were similar between body fat groups (with the exception of palmar hands after exercise) despite significant differences in $T_{sk}$. Local votes progressively decreased (cold TS and more discomfort for TC) and this was in line with $T_{sk}$ decrease. At 55, the variation of local votes across the body (within-subject) was correlated with the variation of $T_{sk}$ across the body.

4.3.8. Local skin temperature and blood flow assessment

$T_{sk}$ relies on the dynamic interplay of heat production and heat loss where regional internal and external parameters play important roles. Finger tip and inside forearm are regions where fat deposits are limited and cutaneous blood flow, as an internal parameter, may largely influence $T_{sk}$.

There was an overall effect of body-fat on finger tip $T_{sk}$ ($p<0.05$) with values for HF being higher than LF and MF, and this was especially pronounced after 20 minutes of exercise as seen on Figure 4.15.

![Figure 4.15](image)

**Figure 4.15.** Evolution of finger tip skin temperature (°C) and finger tip superficial blood flow (Laser Doppler perfusion units) for Low-Fat group (LF) Mid-Fat group (MF) and High-Fat group (HF).

^ significantly different from LF at $p<0.05$, * significantly different from MF at $p<0.05$

Error bars are not reported for clarity for superficial blood flow.
The rise in $T_{sk}$ was preceded by the rise in finger blood flow by 5 minutes and the magnitude of change in finger $T_{sk}$ was much larger for HF group ($\Delta T_{sk} = 17^\circ C$) compared to the limited rise for LF and MF ($\Delta T_{sk} = 2^\circ C$). The rise in finger $T_{sk}$ for the HF group between 15 and 30 was linked to the dynamics of only one participant (BESU). High values for finger blood flow during this phase correspond to only two participants in the group (BESU and MAKI). Finger rewarming (difference 90-55) correlated well with $\bar{T}_{sk}$ ($r = -0.85$, p<0.01) or $T_{re}$ ($r = 0.71$, p<0.01) at the end of exercise (90).

Forearm $T_{sk}$ and superficial blood flow were similar between the three groups (Figure 4.16). The low sample size in the HF group may have prevented $T_{sk}$ differences to be significant during exercise. Unlike the data for the fingertip, the increase in forearm blood flow was not associated with a rise in forearm $T_{sk}$.

⚠️ In summary, finger blood flow was mainly restored in HF (from 20 to 400 LD units) at the end of exercise leading to a marked increase in finger tip $T_{sk}$. 

**Figure 4.16**: Evolution of inside forearm skin temperature (°C) and inside forearm superficial blood flow (Laser Doppler perfusion units) for Low-Fat group (LF) Mid-Fat group (MF) and High-Fat group (HF). Error bars are not reported for clarity for superficial blood flow.
On the other hand, the rise of forearm blood flow was smaller and similar for all body fat groups during exercise (from 20 to 80 LD units) and not accompanied with a rise in forearm $T_{sk}$.

**4.3.9. Local skin temperatures and local body fat parameters:**
The present section highlights regression analysis performed using either individual data for one body region only (between-subjects) or using group averages for various body regions (between-regions).

**4.3.9.1. Local skin temperature and local skinfold thickness**
Table 4.5 summarises the correlation coefficients describing the between-subject relationships between local skin temperature ($T_{sk,local}$) and local skinfold thickness ($SFT_{local}$) for every region investigated. A total of 17 corresponding regions for $T_{sk}$ and SFT were obtained from the 24 skinfold sites (some regions are combinations of sites).

**Table 4.5.** Linear correlation coefficient table (r values) for the relationship between local skin temperature and local skinfold thickness at the different protocol stages (PRE, 0, 15, 55, 90, POST) for the 17 regions under investigation. The cell colour indicates the $p$ value for each correlation coefficient.

<table>
<thead>
<tr>
<th></th>
<th>forearm ant.</th>
<th>biceps</th>
<th>shoulder</th>
<th>pectoral</th>
<th>clavicular</th>
<th>ExternOblique</th>
<th>UpperAbdom</th>
<th>suprailiac</th>
<th>abdominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRE</td>
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<td>-0.62</td>
<td>0.14</td>
<td>-0.70</td>
<td>-0.73</td>
<td>-0.87</td>
<td>-0.78</td>
</tr>
<tr>
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<td>-0.52</td>
<td>-0.80</td>
<td>0.13</td>
<td>-0.63</td>
<td>-0.79</td>
<td>-0.87</td>
<td>-0.81</td>
</tr>
<tr>
<td>15</td>
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<td>-0.72</td>
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<td>-0.64</td>
<td>-0.20</td>
<td>-0.78</td>
<td>-0.89</td>
<td>-0.90</td>
<td>-0.71</td>
</tr>
<tr>
<td>55</td>
<td>-0.02</td>
<td>-0.67</td>
<td>-0.61</td>
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<td>-0.78</td>
<td>-0.80</td>
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<td>-0.62</td>
</tr>
<tr>
<td>90</td>
<td>-0.22</td>
<td>-0.77</td>
<td>-0.65</td>
<td>-0.70</td>
<td>0.26</td>
<td>-0.83</td>
<td>-0.81</td>
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</tr>
<tr>
<td>POST</td>
<td>0.20</td>
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<td>-0.36</td>
<td>-0.66</td>
<td>0.13</td>
<td>-0.79</td>
<td>-0.79</td>
<td>-0.81</td>
<td>-0.68</td>
</tr>
</tbody>
</table>

**POSTERIOR UPPER BODY**

<table>
<thead>
<tr>
<th></th>
<th>scapular</th>
<th>triceps</th>
<th>forearm post</th>
<th>infrascapular</th>
<th>hip</th>
<th>thigh</th>
<th>patella</th>
<th>calf</th>
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</thead>
<tbody>
<tr>
<td>PRE</td>
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<td>-0.33</td>
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<td>-0.71</td>
<td>-0.37</td>
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<tr>
<td>15</td>
<td>-0.42</td>
<td>-0.58</td>
<td>-0.19</td>
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<td>-0.87</td>
<td>-0.69</td>
<td>-0.18</td>
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<tr>
<td>55</td>
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<td>-0.87</td>
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</tr>
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<td>-0.89</td>
<td>-0.69</td>
<td>0.13</td>
<td>-0.74</td>
</tr>
</tbody>
</table>

Figure 4.17 is an illustration of the between-subject relationship at one single site (Infrascapular in the anterior upper body) at three different stages of the protocol (0, 55, 90).
Figure 4.17: Infrascapular skin temperature (°C) in relation to local skinfold thickness (mm) at the infrascapular site for the three main stages of the protocol (0, 55, 90) between subjects. ** significant at p<0.001. Every data point is a participant.

Similarly to Figure 4.7, the slope of the relationship is modified during exercise and resulted in the larger surface cooling for fatter participants.

Interestingly, the strength of the correlation at a specific region was more pronounced the larger the SFT of that specific site was, as shown in Figure 4.18.

Figure 4.18: Correlation coefficients ($r$ values) for each individual location’s relationship between local skin temperature and local skinfold thickness, in relation to the group average local skinfold thickness (mm) for that location *significant at $p<0.05$. Every data point is a skin location (see labels).
From Table 4.5 and Figure 4.17, it can be stated that local SFT explains local $T_{sk}$ differences between participants for most regions (except for clavicular, forearm ant., forearm post., patella). Moreover, the larger the SFT the stronger the correlation was between $T_{sk,local}$ and $SFT_{local}$ at that site (Figure 4.17). This means $T_{sk,local}$ was even more inversely associated with the local subcutaneous fat thickness.

Using a between-regions approach (group average for various regions), it was shown that the local $T_{sk}$ distribution was not determined by the local SFT distribution (Figure 4.19).

![Figure 4.19: Group average local skin temperature (°C) in relation to group average local skinfold thickness (mm) for all corresponding regions for the three main stages of the protocol (0, 55, 90). P>0.05. Every data point is a skin location.](image)

This finding of the relationships between regions was consistent for the three body fat groups separately (at 55, $r = 0.18$ for LF, $r = 0.14$ for MF, $r = -0.11$ for HF) and most importantly consistent with every individual (maximal $r = 0.40$). In other words, the $T_{sk}$ body maps were not explained by the distribution of SFT over the body neither at rest nor during exercise for any individual.

**4.3.9.2. Local skin temperature variance and local skinfold thickness**

In this section, the $T_{sk}$ variance over a body region is considered for every individual. Variance is not the inter-individual variability in local $T_{sk}$ between participants but the actual variations in temperatures within a single region computed for each participant. Local SFT remains the same parameter as in 4.3.8.1. Table 4.6 summarises the correlation coefficients describing the between-subject
relationships between local $T_{sk}$ variance and local skinfold thickness for every body regions investigated.

**Table 4.6.** Linear correlation coefficient table (r values) for the relationship between local skin temperature variance and local skinfold thickness at the different protocol stages (PRE, 0, 15, 55, 90, POST) for the 17 regions under investigation. The cell colour indicates the $p$ value for each correlation coefficient.

<table>
<thead>
<tr>
<th></th>
<th>FOREARM</th>
<th>FOREARM</th>
<th>BRAZILIAN</th>
<th>CLAVICULAR</th>
<th>EXTERNAL OBlique</th>
<th>UPPER ABDOMEN</th>
<th>SUPRAINFRACRICA</th>
<th>ABDOMEN</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PRE</strong></td>
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<td></td>
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<tr>
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<td>0.53</td>
<td>0.69</td>
</tr>
<tr>
<td>15</td>
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<td>0.24</td>
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<td>-0.01</td>
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<td>55</td>
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<td>0.38</td>
<td>0.18</td>
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</tr>
<tr>
<td>90</td>
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<td>-0.74</td>
<td>0.42</td>
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<td>0.14</td>
<td>0.77</td>
<td>0.38</td>
<td>0.76</td>
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<tr>
<td>POST</td>
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<td>0.10</td>
<td>0.72</td>
<td>0.44</td>
<td>0.77</td>
</tr>
</tbody>
</table>

The correlations between local $T_{sk}$ variance and local SFT were not as consistent as the ones with local $T_{sk}$ (Table 4.4), and limited to regions with high fat deposits (suprailiac, infrascapular, pectoral) with mainly positive relationships, i.e more subcutaneous fat thickness producing a larger variance in the segment between our participants.

Using a between-regions approach (group average for various regions), it was shown that the $T_{sk}$ variance distribution within a region was determined by the local SFT distribution (Figure 4.20).

![Graph 4.20](image)

4.20. Group average local skin temperature variance (°C) in relation to group average local skinfold thickness (mm) for all corresponding regions for the three main stages of the protocol (0, 55, 90). * significant at $p<0.05$. Every data point is a skin location.
This was consistent for the LF and MF body fat groups separately and consistent with most individuals within these groups. Interestingly, this relationship was stronger when anterior upper body sites were isolated for the analysis (e.g. r = -0.89 at 55)

- In summary, SFT<sub>local</sub> explained the inter-individual variability in T<sub>sk,local</sub> and the negative relationships were even more pronounced in regions of high fat deposits (e.g.: hip). On the other hand, the distribution of SFT<sub>local</sub> did not explain the intra-individual variability of T<sub>sk,local</sub> but it was yet associated with the T<sub>sk</sub> variance within body regions.

4.3.10. Local skin temperatures and mean skin temperature

A large variety of T<sub>sk</sub> was obtained throughout a protocol combining resting phase in 10 and 22°C as well as exercising at 10°C. It was judged interesting to look at the best local predictor for mean skin temperature at any time point. The hypochondriac, scapular and hamstrings regions (#10, #20 and #26) predicted T<sub>sk</sub> best.

\[
\text{Eq. } T_{sk} (°C) = 1.03 \times T_{sk, hypochondriac} - 1.37 \quad (r = 0.97)
\]

\[
\text{Eq. } T_{sk} (°C) = 0.90 \times T_{sk, scapular} + 2.04 \quad (r = 0.98)
\]

\[
\text{Eq. } T_{sk} (°C) = 0.89 \times T_{sk, hamstrings} + 3.80 \quad (r = 0.98)
\]

The standard error of estimate (SEE) was 0.59°C, 0.50°C and 0.50°C respectively with an agreement frequency of 67%, 67% and 78% (within ±0.5°C) and of 88%, 88% and 94% (within ±1.0°C).

Another interesting analysis was to look at the actual body region that could closely reflect T<sub>sk</sub> without any correction. The advantage of the mapping approach was then fully utilized by averaging the relative maps of different groups and stages all together. The final relative map displays the regions most representative to T<sub>sk</sub> over the whole protocol (Figure 4.21). The consistency of this pattern was analysed through a map displaying the pixel by pixel standard deviations of all these relative maps taken together. The regions close to 1 with the smallest standard deviation would therefore be the best predictor of T<sub>sk</sub>

After a careful pixel by pixel analysis; it was found that a site of the pectoral region was one of the best region representing mean skin temperature (i.e value = 1 and
minimum deviation across conditions) as shown on Figure 4.22 and this can easily be reported on a normal man using surface anatomy (Figure 4.23). Other points could also be selected with values close to 1 and small deviations but this point selected also correspond to an easy accessible and practical body location. There is virtually no need to apply correction on this point considering its value of 1.00 in relative $T_{sk}$ and its deviation across the 6 conditions (SD rel. $T_{sk} = 0.01$; see Fig. 4.22).
Figure 4.21. Relative maps of skin temperature averaged for all groups and all stages (average of 18 maps = 6 stages*3 groups) showing the regions best predicting mean skin temperature over the whole protocol for all individuals (left). Standard deviations of the 18 relative maps (right).
Figure 4.22: Relative map of skin temperature (anterior torso) averaged for all groups and all stages (average of 18 maps) showing the regions best predicting mean skin temperature over the whole protocol for all individuals (left). Standard deviations of the 18 relative maps (right).

Figure 4.23: Picture of the location (red) that best represents mean skin temperature during semi-nude active and inactive cold exposure with no air velocity.

Using surface anatomy, this anatomical landmark can easily be described at one third from the base of the armpits (horizontal extension of the nipple) to the jugular notch.
4.4. Discussion

The aim of the present study was to further explore the effect of skinfold thickness on the $T_{sk}$ distribution patterns during cold exposure based on a population with a large range of body fat. This investigation was done at two levels of metabolic heat production. Following the initial hypothesis, the main findings are presented below:

1. An inverse relationship was found between $\bar{T}_{sk}$ and overall body fat (%BF and total sum of skinfolds) on one hand, and $T_{sk,local}$ and $SFT_{local}$ on the other, both at rest and during exercise.

2. $T_{sk}$ patterns did not reflect the corresponding subcutaneous fat thickness pattern. The thermal patterns were relatively similar between the LF and MF groups and the HF group exhibited some specific features especially during exercise in the lower back, sternal and face regions.

3. The $T_{sk}$ variations between regions across the body explained the variations of thermal sensation votes but only during the resting phase. Despite differences in $T_{sk,local}$ and $\bar{T}_{sk}$, all body fat groups had the same perceptual responses.

4. Changes in blood flow induced by exercise did not modify the whole-body thermal pattern. Cutaneous blood flow only correlated with $T_{sk,local}$ at the fingertip but not at the forearm.

4.4.1. Relationship between skin temperature and body fat parameters

Adiposity ranged from 6.6 to 40.2% which exceeds 10$^{th}$ and 90$^{th}$ percentile of published normative values for this age group (Whaley et al., 2006). Despite the low number of participants in the high-fat category, a wide continuum of body fat contents was obtained, meeting the recruitment target. Fat patterning for all body fat groups strongly reflected the anatomical placement of adipose tissue around the abdominal region, in line with the generalized android fat distribution for males (Mueller et al., 1985).
4.4.1.1. Mean skin temperature and overall body fat content
A strong and consistent negative correlation was found between mean skin temperature ($\overline{T}_{sk}$) and body fat percentage (Figure 4.7) and this was similarly true for total sum of skinfold or mean skinfold thickness (almost identical $r$ values). Baker and Daniels (1956) also found a strong correlation between $\overline{T}_{sk}$ and %BF for a population of 31 military males (2-18%BF, 19-42 years) at rest for 2 hours in a 15°C environment. It reached $r$ values of -0.72 after 60 minutes of exposure and -0.81 after 120 minutes. Correlation coefficients in the present study were higher even pre and post-exposure (from $r = -0.84$ to $r = -0.91$) which can stem from the larger body fat range and the colder exposure. Our results are also in line with the pioneering work of LeBlanc (1954) with a 60-min exposure at 10°C of 6 males of differing body fat, and similar to Oksa et al. (1993) with a $r = -0.79$ for 10 males (7.8-16.7%BF) at 10°C for 60 minutes. Hypothesis (1) was therefore accepted for overall parameters stating that an inverse relationship would exist between $T_{sk}$ and body fat.

4.4.1.2. Local skin temperature and local subcutaneous fat thickness
A total of 17 regions were investigated using the local skin temperature ($T_{sk,local}$) determined from the whole-body segmentation and the corresponding underlying skinfold thickness ($SFT_{local}$) obtained by skinfold calliper. A negative relationship between $T_{sk,local}$ and $SFT_{local}$ was found for 12 regions and this was consistent throughout the entire protocol including the exercise period and pre/post exposure. The remaining 5 regions exhibited non significant correlations yet also negative for a large majority as seen in Table 4.5. These were body segments with limited fat deposits or bony surfaces close to the skin (patella, clavicular, forearm, scapular).

Overall, it can be concluded that hypothesis (1) was also accepted for several body regions with variations in $T_{sk,local}$ between individuals associated with variations in $SFT_{local}$ at rest and during exercise in the cold. Several studies have reported the same conclusion, though limited to the chest and arm (Baker and Daniels 1956), the abdomen and the lower back (Frim et al. 1991), the abdomen and chest (LeBlanc 1954). Our investigation extends this conclusion to several more detailed body regions. A between-regions analysis interestingly revealed that the negative correlation between $T_{sk,local}$ and $SFT_{local}$ at each region was accentuated at the body region with larger SFT (Figure 4.18), this had never been done before.
Lastly, it is important to note that $T_{sk}$ variance within a single region gradually became larger towards the end of the cold exposure. By changing the environmental conditions (28°C, 23°C, 19°C), Frim et al. (1990) also obtained the same finding. This point-to-point variation in $T_{sk}$ for individual regions was however not correlated with SFT$_{local}$ except for 3 regions (suprailiac, infrascapular, pectoral). For the remaining 14 regions, the point-to-point variation in $T_{sk}$ did not depend on the thickness of the fat deposits which is in agreement with Frim et al. (1990). They speculated that the shape and size, rather than the thickness of the fat pads, are the important characteristics causing the variations in temperature. It is suggested that a technique such as computed tomography (combined frontal and sagital 2D scans) would be helpful in order to understand the three-dimensional aspects of the fat deposits.

- During a cold exposure, $T_{sk}$ differences between individuals can be explained by the anthropometrical differences in subcutaneous fat globally (%BF $\Rightarrow$ $\overline{T}_{sk}$) as well as locally (SFT$_{local}$ $\Rightarrow$ $T_{sk,local}$). The correlation between $T_{sk,local}$ and SFT$_{local}$ was stronger at the regions with large skinfold thickness. The $T_{sk}$ variance within a region decreases with increasing SFT$_{local}$ for different regions.

4.4.2. Body maps of skin temperatures

4.4.2.1. Body maps during inactive cooling

To the best of our knowledge, the evolution of $T_{sk}$ over a cooling protocol has never been done using average body maps in the literature. This original approach brings some new insights in the topography of skin cooling. One of the main finding from the absolute body maps (Figure 4.9 to Figure 4.11) was that surface cooling was always initiated in the legs, followed by the abdomen and pectorals and this progressively extended (over the course of 55 minutes) to the arms and back (flanks). Moreover, the three body fat groups cooled to the same extent and in a similar topographical way over the seated exposure despite different initial temperatures. This simply resulted in a time delay before a body fat group reached as low absolute $T_{sk}$ as the group with higher adiposity. For example, the absolute body map for LF group at 55 was similar than the one for MF group at 15.
Overall, the $T_{sk}$ difference between the warmest and the coldest region increased from PRE (5.3±0.9°C) to 55 (10.5±1.3°C). Cooling was relatively homogenous for all groups across regions with an average for all participants of 3.7±1.3°C and extreme cooling in the hands (8.4±1.1°C) and forearm (5.5±0.6°C) and the lowest cooling for the clavicular region close to the core (1.9±0.6°C). This observation was consistent with the cephalo-caudal distribution of $T_{sk}$ (colder towards the extremities; Candas, 2005).

The inactive absolute $T_{sk}$ body maps could be compared with only few other published individual thermograms. Clark and Edholm (1985) presented a moderately fat male resting at 10°C (for an unknown period) with a 10°C difference between minimal and maximal temperatures. This difference and the absolute $T_{sk}$ map agreed well with our data. Local absolute differences in $T_{sk,local}$ between body fat groups (Table 4.2) were mostly observed in the abdominal regions, back, anterior upper arms and thighs which corresponded to regions with large fat deposits differences. This was in line with the previous analysis over the full body fat range (see 4.4.1.2).

The presentation of relative $T_{sk}$ body maps was also a good way to highlight the cephalo-caudal distribution (Candas, 2005) and its consistency between groups and across time (Figure 4.9 to 4.11). As they take into account the group’s $\overline{T}_{sk}$ at a specific stage, it becomes possible to emphasize the presence of specific consistent features between groups such as:

- a V-shape of $T_{sk}$ close to $\overline{T}_{sk}$ over the anterior upper body
- a V-shape of warmer $T_{sk}$ for the posterior upper body (specifically warmer along the spine) with a medio-lateral drop in $T_{sk}$ towards the colder hip
- a difference between the anterior and posterior upper body (colder posterior)
- a difference between the colder patella and the warmer popliteal fossa
- a difference between the colder nose and the warmer orbital regions

The V-shape over the anterior torso was topographically similar to the shape obtained after 40-min running (see Chapter 3, Figure 3.6) with lower absolute $T_{sk}$ in the previous study, mainly due to the added front air velocity. Furthermore, the discrete cold regions over the pectoral and nipple together with the warmer sternal and thyroid regions (defining a V-shape over the anterior upper body) were similar to what observed on a representative thermogram after 60-min rest at 18°C in
Livingstone et al. (1987). The contrasts between regions in our data are also in very good agreement with the conclusions from Veghte (1965) based on 15 semi-nude males resting for 2 hours in a 4°C environment.

Differences in relative $T_{sk}$ between groups (Table 4.3) were mostly found in the extremities such as the lower arms, lower legs, face (low fat deposit) and the lower back, especially the hip (high fat deposit). An important finding was that the overall $T_{sk}$ distribution was quite similar between LF and MF groups and differed only slightly with HF group, though the main features presented above were present.

### 4.4.2.2. Body maps following exercise

A clear distinction in **absolute** $T_{sk}$ between LF/MF groups and HF group appeared following the cycling exercise. $T_{sk}$ for the HF group continued to fall for all regions except for the hands and fingers (Fig. 4.12 and 4.15) whereas the LF and MF groups displayed a combination of regions with lower and higher $T_{sk}$ compared to pre-exercise.

The absolute differences between groups were highly pronounced in the back and abdominal regions (Table 4.2). In the HF group, the lower surface temperatures increased the core-to-skin resistance and some evaporative heat loss occurred throughout the exercise (for 2 participants out of 4). This was however not sufficient to counteract the metabolic heat production leading to an immediate rise in $T_{re}$ (Figure 4.4). Their low surface area-to-mass ratio in the context of increasing body heat content was a disadvantage for heat dissipation as well as the lower specific heat of fat tissues. The important blood supply to the extremities (Figure 4.15) triggered after 10 minutes of exercise was also not sufficient to alleviate the heat strain (see 4.4.3.3).

On the other hand, body heat content redistribution imposed by cycling tended to decrease $T_{re}$ at the onset of exercise in LF and MF by mixing blood from the cooled limbs with the warm core as found elsewhere (Hong and Nadel, 1979). Their advantageous larger $A_{DU}/M$ and thin tissue insulation favoured heat dissipation by dry heat loss (at the same workload as HF), especially through the active muscles. Regions of higher $T_{sk}$ indeed located over the active legs and the posterior upper arms. This feature is consistent with conclusions presented by Clark et al. (1977) and Veghte et al. (1979) based on individual thermograms.
The body maps of relative $T_{sk}$ mainly indicate that $T_{sk}$ distribution for the upper body remained consistent following exercise (Figure 4.12) with only slight differences between groups at the face and hip (Table 4.3). Within the HF relative body map (Figure 4.12), the area over the face displayed much warmer temperatures compared to the group $T_{sk}$ explaining the large contrast with the rest of the chest. Overall, the absolute temperature difference was however significantly lower in HF (8.6±0.6°C) than both LF and HF (12.1±1.9°C, 11.9±2.0°C). The colder pectoral and abdominal regions (V-shape isotherm) for all groups were in line with the thermograms of a cycling man (50W) at 10°C (Torii et al. 1992). The lower body $T_{sk}$ distribution differed with the rewarming of thigh and hamstrings (LF) on one hand, and the rewarming of the chin and calves (HF) on the other hand. This finding is original and will be discussed in 4.4.3.2.

Over the whole body, the topography of $T_{sk}$ changes only to a small extent and this was in good agreement with data from Werner et al. (1985).

4.4.3. Mean skin temperature using a single region within the body map
In our experiment, the best predictor regions for $T_{sk}$ were the popliteal fossa and epigastric region. These single sites are different than the medial thigh which has been suggested to be a fair approximation of $T_{sk}$ for non working persons (Teichner, 1958; Ramanathan, 1964; Veghte, 1965). It was interesting to note that the formula for calculation of $T_{sk}$ proposed by Nielsen et al. (1984) and Ramanathan (1964) applied to our results also reached good agreement frequencies: 89% and 97% (within ±1.0°C). Stepwise regression analysis could be performed to produce new weighted equations (multi-sites) for $T_{sk}$ prediction from our results. They could be validated using the database obtained within the framework of the present research work. The absence of air velocity and the nude exposure are potential limitations for the application of new equations towards other environments, but these limitations may also apply to existing equations for the prediction of $T_{sk}$.

Interestingly, the analysis of our various relative maps managed to provide a specific localised single spot for the accurate measurement of $T_{sk}$ (value equal to $T_{sk}$ with low standard deviation across body fat groups and time). A proposed practical region
is located in the pectoral region, one third on a line from the armpit and the jugular notch.

- Consistent features of the resting thermal patterns (e.g. V-shape isotherms) between groups were observed despite the relatively constant absolute difference in $T_{sk}$. Exercise induced an important rewarming of the active legs and posterior upper arms for moderately to low body fat participants whereas an important rewarming occurred only in the hands and fingers for the high fat group.

- A single spot, accessible and easily identified, that best predicts $T_{sk}$ based on our data is located in the pectoral region. This could be used with no correction as a single point measurement instead of multi-sites weighed equations in semi-nude experiments.

4.4.4. Skin temperature distribution and underlying factors
A specific focus of the present study was to examine the potential contribution of various factors in the $T_{sk}$ distribution across the body. Werner and Reents (1980) highlighted the importance of understanding the spatial distribution of variables involved in the thermoregulatory system due to their local influence. Apart from the work reported by Webb (1992) and performed in 1972, no specific whole-body approach had been used since the 1980’s and the present work aims at extending this knowledge with the use of infrared thermography and a new processing technique to visually display a temperature continuum of the entire body for a large population.

4.4.4.1. Skinfold thickness distribution
The relationship between the $T_{sk,local}$ distribution and the $SFT_{local}$ distribution was not significant (Figure 4.19) neither at rest nor during exercise. This was a novel finding for participants at rest in conflict with the pioneering assumption made by LeBlanc (1954) that “variations of fat thickness over the body explain to a certain extent the regional variations of $T_{sk}$”.

Hypothesis (2) stating that the thermal pattern would reflect fat thickness patterning over the body is therefore rejected. Other factors must be involved in the explanation of inter-regional variations in $T_{sk}$.

A secondary finding using between-regions analysis was that $T_{sk}$ variance within a region decreased with increasing SFT across the body (Figure 4.21). In other words, the point-to-point variation in $T_{sk}$ was lower over large fat deposits across the body.
The accumulation of adipocytes in males preferably targets the regions defining the android fat patterning with the hip, suprailiac and abdominal regions. It can be suggested that the fat pads in these region tend to be more geometrically homogenous (in their bi-dimensional configuration) so that surface temperature impacted by core-to-skin heat flow would in turn be less variable. As indicated by Livingstone et al. (1987), this may have some important implications in the placement of skin sensors for the calculation of $\bar{T}_{sk}$.

### 4.4.4.2. Muscle insulation and muscle heat production

Vasoconstricted muscles have been found to significantly contribute to total body insulation (Veicsteinas et al., 1982, Park et al., 1984) though this was mainly observed during water immersion. During exposure to cool air temperature (20°C), Jequier et al. (1974) found individuals with a tendency towards obesity to have higher total body insulation and a greater reliance on non-fat insulation. From a qualitative surface anatomy analysis, it can be suggested that the $T_{sk}$ patterns reflected well the position of the large superficial and deep body muscles such as the pectoral and abdominal muscles (defining the V-shape for the anterior body) and the trapezius and latissimi dorsi (defining the V-shape for the posterior body).

![Figure 4.24](image1.png)  
![Figure 4.24](image2.png)

**Figure 4.24.** Comparison of skin temperature mapping for Mid-Fat group (MF, $n=8$) at the end of the resting cold exposure with surface anatomy drawings representing the location and name of the body muscles.

As proposed by Anderson (1999), the contribution of peripheral musculature to body insulation depends upon the anatomical site investigated and the rate of tissue perfusion.
The insulation of the back muscles may be limited due to a dense vascularisation, especially along the spine with the intra-vertebral venous plexus (Hoogland et al., 2012). The muscles also become thinner towards the spinal cord with the insertion of connective tissues. For these reasons, the posterior upper body displayed higher Tsk despite similar subcutaneous fat thickness and the presence of large muscles. It would be interesting to further explore the muscle contribution to Tsk by using magnetic resonance imaging (MRI), computed tomography (CT) or ultrasound imaging (USI) in order to determine fat as well as muscle thickness within a body region (Ishida et al., 1997). It seems unlikely that the isotherms defined over muscles correspond to shivering thermogenesis as these were also observed in a 22°C environment and in all our participants (with or without initiated shivering).

During exercise, heat is produced in the vicinity of the muscle fibres and conveyed to the periphery with the blood stream through convective heat transfer or even directly radially by conduction between the muscle, subcutaneous and skin tissues. This mechanism became apparent for all groups in the quadriceps and calves, for the LF in the hamstrings (Fig 4.11). Regarding the topography of heat production, Werner and Reents (1980) were limited by the technologies at the time with only surface electromyography and the problems of a discrete assessment. Recently, Masud et al. (2009) presented whole-body maps of glucose metabolism at different cycling workloads (Figure 4.25) using $^{18}$F-2-fluoro-2-deoxyglucose and 3D Positron Emission Tomography ($[^{18}F]$FDG-PET).

Figure 4.25. Comparison of metabolic mapping from 5 males at rest and during cycling (40 and 70% $VO_{2\text{max}}$) (from Masud et al. 2009) with the relative skin temperature mapping before (55) and after cycling at 50% $VO_{2\text{max}}$ (90) for Low-Fat group (LF, n=8) (our results)
As a sole indication, the glucose utilization rate increased 4 times at 40 and 70% \( \dot{V}O_{2,\text{max}} \) in the thigh muscle (Masud et al., 2009) as \( T_{sk} \) after 30 minutes at 50% \( \dot{V}O_{2,\text{max}} \) raised by 2.0°C over the thigh region (our data). It is however not yet clear what is the exact association between glucose utilization rate and heat production but from the energy cascade involved in power production, it can be hypothesized that they must be related.

The thin fat insulation in HF together with the potentially lower muscle mass (producing the same amount of heat) may explain the larger rewarming in this group. Infrared thermography could be an indication of heat production patterns by comparing pre and post-exercise using relative maps. Sometimes this heat production may only prevent the drop in \( T_{sk} \) compared to the other body regions.

4.4.4.3. Local tissue perfusion
Laser Doppler flowmetry was used to assess skin blood flow. This technique has been shown to produce values in proportion to those obtained by other methods especially plethysmography (Johnson et al., 1984). Our primary main finding was that skin blood flow at the finger and forearm was similar between all body fat groups during the resting exposure with a marked vasoconstriction. A similar increase in forearm blood flow was observed during exercise between groups whereas a large rise in finger tip blood flow occurred only for the HF group after 15 minutes of exercise. This was associated with a larger increase in finger \( T_{sk} \) for HF (from 20 to 400 LD units). In terms of dynamics, our secondary finding was that there was a good agreement between skin blood flow and \( T_{sk} \) at the finger tip but this was not the case at the forearm. Forearm skin blood flow increased 4 times during exercise but there was no subsequent increase in forearm \( T_{sk} \). On the other hand, finger tip blood flow increased 4 times for LF and MF with a rise in finger temperature by 2°C and it increased 10 times in HF with a subsequent finger \( T_{sk} \) increase of 16°C (Figure 4.15) and 4°C in palmar hand temperature (Figure 4.14).

This specific feature is in line with findings by Savastano et al. (2009) indicating that obese people favoured heat dissipation through the extremities and this may offset heat retention in body regions with greater adiposity to maintain normothermia in a thermoneutral environment. Our results tended to extend this finding during exercise in a cold environment but heat dissipation through the hands and fingers in the HF group was clearly not sufficient to offset the rise in \( T_{core} \) (Figure 4.4). This rise was
associated with the release of the vasoconstrictor tone leading to an opening of the arteriovenous anastomoses in the previously cooled hands (Wyndham, 1951). Aita and Yoshizumi (1994) also observed a quicker temperature response to the thermal load due to exercise for fat compared to thin subjects.

The 5 minutes time delay between the increase of perfusion and rise in $T_{sk}$ was in agreement with Goetz (1947). Inter-individual differences in $\dot{V}O_{2,max} \cdot \% \dot{V}O_{2,max}$ or $T_{re}$ increment were not related to the marked interindividual differences in finger rewarming, in line with Hellström et al. (1970). It seems to be more associated with the absolute $T_{re} (r = 0.71, p<0.05)$ or $T_{sk} (r = -0.85, p<0.01)$.

The early rise in forearm blood flow (Figure 4.16) before exposure (PRE5, 0) before exercise (55, 60), after exposure (POST15) corresponded to a change in the participant’s posture from sitting (with both hands resting on stools) to standing for the infrared measurements. The importance of posture on skin blood flow is significant as highlighted by Wright et al. (2006) with an increase in sympathetic efferent nerve activity inducing an increase in the peripheral vascular tone. The modifications in posture did not affect finger blood flow because fingers are part of acral regions with many arteriovenous anastomosis solely driven by variations of the vasoconstrictor tone.

Our skin blood flow measurements were limited to two regions in the limbs. Werner and Reents (1980) investigated the blood flow response with a fluvographic method in the trunk, arm, and leg at rest (10°C environment). They found that regional differences in blood flow appeared to be very small. Another investigation by the same research group (Hunold et al., 1992) revealed that warmer $T_{sk}$ was constantly correlated with higher blood flow in the thigh region. This was true in our data for the finger tip region. Moreover, they suggested that the circulatory heat transfer dominates the pattern of temperature distribution after exercise. The hypothesized central reaction to the heat load is in contrast with our results as there was no correlation between $T_{sk}$ and skin blood flow at the forearm and there was no apparent redistribution of blood flow in other regions. Our colder environment (10 vs 23°C) may explain the discrepancy. Therefore, the prevalence of local muscle heating due to a conductive process can not be ruled out (4.3.2).

Lastly, a large influence of the blood flow on the $T_{sk}$ distribution across the body can be seen in the sternal, thyroid and orbital regions. It is indeed clear from absolute and
relative body maps that these regions displayed the highest $T_{sk}$ and cooled the least over the exposure either at rest or during exercise. The location of the heart and the routes of the subclavian vessels, the jugular veins, carotid arteries and angular vessels define a large region of warmer temperature than the surrounding which is consistent throughout the exposure. Interestingly, the route of the brachial artery became also apparent towards the end of exposure especially for LF and MF (see Figure 4.11).

- $T_{sk}$ patterns across the body did not reflect the skinfold thickness pattern. It can be hypothesized that muscle thickness may play a role in the $T_{sk}$ distribution. The thermal patterns differed only slightly between groups at rest and different responses occurred during exercise. Exercising muscles were observed in the cycling thermal pattern with the hands and fingers involved in heat dissipation for the HF group. A dynamic interplay between heat production (muscle), heat transfer (vasomotor adjustment, tissue insulation) and heat loss (evaporation and convection) is necessarily involved locally to explain the $T_{sk}$ regional variations.

### 4.4.5. Subjective responses
The absence of significant differences between body fat groups for both TS and TC votes (local and overall) was the main finding. Linked to this conclusion, there was no correlation between individual body fat content and individual overall thermal sensation and comfort.

Our results contrast with several studies (Baker and Daniels 1956, Buskirk et al., 1963, Budd et al., 1991) which found fatter males to express less discomfort and warmer sensations than their leaner counterparts. Budd et al. (1991) even reported a significant positive relationship between the average skinfold thickness and overall thermal sensation after 2 hours of 10°C exposure for 12 minimally clothed males (14.8-35.9%BF). This was also shown for females (15-35%BF) through inverse relationship between percentage body fat and overall sensation after 60-min of exposure at 5°C (Glickmann-Weiss et al., 1998) with more marked differences at the start of exposure (warmer sensation for fatter subjects).

Although not significant, $TS_{overall}$ tended to be warmer following exercise for the HF group, which was in agreement with the larger rate and absolute rectal temperature.
Discomfort correlates best with lowering $T_{sk}$ in the cold for seated unclothed or clothed subjects (Gagge et al., 1967; Pellerin et al., 2004). The agreement was largely increased when the exercise stage was removed of the relationship between the dynamics of $T_{sk}$ and sensation or comfort votes.

Similar to temperature and fat thickness mapping, the advantage of the present study was to offer an extensive perceptual mapping with $TS_{local}$ and $TC_{local}$ over 11 regions. The only difference between groups of this regional investigation was found in the arms and hands with significantly warmer sensation and lower discomfort for the HF compared to the two other groups at the end of exercise. This was clearly associated with physiological changes occurring in the extremities during exercise (Figure 4.5). Before the exercising phase, $TS_{overall}$ consistently followed the lowest local thermal votes (lower back and palmar hands) which is in line with the complaint-driven model developed by Zhang et al. (2010) $TC_{overall}$ was associated with several low $TC_{local}$, not entirely in line with the local origin of cold discomfort with more than 3 body parts sensed as uncomfortable (Pellerin et al. 2004).

Locally, there was also no correlation between $TS_{local}$ and $TC_{local}$ and corresponding individual $T_{sk}$ for large body segments considering one specific stage. Despite absolute differences in local $T_{sk}$, sensation and comfort votes were identical within a population comprising a large range of body fat. When all votes for the resting phase were considered, there was however a positive relationship between $TS_{local}$ / $TC_{local}$ and $T_{sk,local}$ at all sites, being the strongest for palmar hands ($r = 0.83$ for TS and $r = 0.81$ for TC $p<0.01$) and lowest for the abdomen ($r = 0.62$ for TS and $r = 0.57$ for TC $p<0.05$). This relationship was weaker considering all votes following exercise (maximum of $r = 0.35$ for TS and 0.39 for TC) at the exception of the palmar hand ($r = 0.58$ for TS and $r = 0.54$ for TC).

Using a within-subject approach (between regions), the variations of $TS_{local}$ and $TC_{local}$ across the body were positively correlated with the variations in regional $T_{sk}$. This was only true at the end of the resting exposure when pronounced inter-regional $T_{sk}$ differences were displayed (average max-min= $10.2\pm0.3$ °C) but not during other stages of the protocol. To our knowledge, this approach has never been used by other researchers and can have valuable implications in monitoring certain types of prolonged exposure.
Furthermore, sensitivity calculations during whole-body cooling (TS\textsubscript{local} / (T\textsubscript{sk,0} - T\textsubscript{sk,55})) revealed that chest, abdomen and anterior legs were the most sensitive regions (for the same change in T\textsubscript{sk}) followed by the upper and lower back and least sensitive regions were the arms, hands, face and posterior legs. No differences were found between groups as all participants cooled to the same extent. These natural cooling data can be observed together with the cold sensitivity study by Stevens \textit{et al.} (1979) applying a discrete stimulus of varying temperatures in the different body parts. They found the trunk region to be most sensitive followed by the limbs and face.

- Perceptual responses were similar for all participants regardless of their body fat. Overall sensation and comfort votes followed the worst local votes at rest. The T\textsubscript{sk} variations explained the variations of thermal sensation votes only during the resting phase.

4.5. Conclusions

The present study was mainly focused on the T\textsubscript{sk} patterns in conjunction with body fat parameters and perceptual responses. The findings can be summarised as follow:

- During a cold exposure, differences in T\textsubscript{sk} between individuals can be explained by the anthropometrical differences in subcutaneous fat globally (%BF $\Leftrightarrow$ $\overline{T}$\textsubscript{sk}) as well as locally (SFT\textsubscript{local} $\Leftrightarrow$ T\textsubscript{sk,local}).

- Consistent features of the resting thermal patterns (e.g V-shape isotherms) between groups were observed despite the relatively constant absolute T\textsubscript{sk} difference. Exercise induced an important rewarming of the active legs and posterior upper arms for moderately to low body fat participants whereas an important rewarming occurred only in the hands and fingers for the high fat group.

- A single spot that best predicts $\overline{T}$\textsubscript{sk} based on our data is located one third of a line between the armpit and the jugular notch. This could be used a single point measurement for $\overline{T}$\textsubscript{sk} instead of multi-sites weighed equations during semi-nude cold exposure.
Tk patterns across the body did not reflect the subcutaneous fat thickness pattern. It can be hypothesized that muscle thickness may play a role in Tk distribution. The thermal patterns differed only slightly between groups at rest and different responses occurred during exercise. Exercising muscles were observed in the cycling thermal pattern with the hands and fingers involved in heat dissipation for the HF group. A dynamic interplay between heat production (muscle), heat transfer (vasomotor adjustment, tissue insulation) and heat loss (evaporation and convection) is necessarily involved locally to explain the regional Tk variations.

Perceptual responses were similar for all participants regardless of their body fat. Overall sensation and comfort votes followed the worst local votes at rest. The Tk variations explained the variations of thermal sensation votes only during the resting phase.
CHAPTER 5

Evolution of skin temperature responses of semi-nude males whilst rowing at 10°C and 20°C: the effect of ambient temperature and exercise type

Chapter Summary

This chapter explores the variations of skin temperature across the body in two different ambient temperatures (10°C and 20°C). It also investigates their temporal variations during a 40-min rowing exercise performed by 8 active males at 60% $\dot{V}O_{2\text{max}}$. Ambient temperature only little affected the skin temperature patterns; however the range of skin temperature across the body became wider in the cold environment (difference between warmest and coldest region) with 8.4°C at 10°C and 6.0°C at 20°C. A mean skin temperature difference of 4°C was observed between the two environments. This led to lower thermal sensations and a significantly lower rate of perceived exertion in the 10°C environment. Skin temperature patterns obtained during rowing provided additional evidence that skin overlying activity-specific muscles is warmer than surrounding tissues which was in line with thermal patterns of other exercise types such as running and cycling (Chapter 3 and 4).

Context

The previous study (Chapter 4) on males with a large body fat range has highlighted the similarities and differences in the skin temperature ($T_{sk}$) distribution at rest and during cycling in the cold. The contribution of local heat production to $T_{sk}$ was observed especially with the low fat group having an increase of $T_{sk}$ overlying the active quadriceps during cycling. Cycling can be classified as non-weight bearing exercise, mainly involving the lower body musculature. In Chapter 3, the body maps of $T_{sk}$ distribution during running displayed warmer skin over the active lower leg.
muscles. Running can be classified as weight-bearing exercise where lower body muscles are primarily important and force production for core stability and arm swing remains minimal. Another exercise type will be relevant to explore in order to provide some more evidence that active muscles are largely involved in $T_{sk}$ distribution during exercise. The dynamic rowing motion seems suitable for the investigation of a whole-body exercise in a non-weight bearing situation other than cycling.

Air temperature ($T_a$) represents a main external $T_{sk}$ determinant which has not been explored in the previous experiments. Applying a mapping methodology to study the influence of $T_a$ will be original, even more so in rowing involving the upper body musculature. The present study will therefore focus on the impact of different $T_a$ on the $T_{sk}$ distribution together with other thermoregulatory and perceptual responses.

5.1. Introduction

The first extensive investigation of the effect of $T_a$ on human $T_{sk}$ dates back from the work of Thomas Bedford (Bedford, 1935) based on 3085 observations of industrial workers. Correlations between forehead, hand and foot temperatures and $T_a$ were obtained in the range of 12°C to 24°C. He notably found that $T_{sk}$ increased by 0.14°C on the forehead, 0.47°C on the hand and 0.81°C on the feet for a rise of 1°C in $T_a$ from 12°C upwards. Early works in the John Pierce Laboratory (USA) gave a larger overview of the variations of $T_{sk}$ over 15 regions the body surface (Winslow et al., 1937; Gagge et al., 1938). Contact measurements were performed across a range of 18°C to 42°C $T_a$, though only based on observations of 2 subjects. Above 32°C $T_a$, they observed very similar $T_{sk}$ for the major body segments and a large heterogeneity between body regions towards the colder environmental temperatures.

With the development of infrared thermography, Vegthe (1965) performed an analysis of 15 nude males in various environments (4°C to 27°C) providing a topography of the $T_{sk}$ distribution. Quantitative $T_{sk}$ values were given for localised regions in a cold, thermoneutral and sweating state at rest. The clear positive correlation between $T_{sk}$ and $T_a$ could be observed with inter-regional differences in 42 body regions as originally highlighted in 3 regions by Bedford (1935). It was clear from Vegthe’s results that $T_{sk}$ across the body tended to be uniform in the hot condition with values around 33°C.
Gagge et al. (1967) and Werner and Reents (1980) performed extensive steady-state and transient measurements on a limited number of participants at rest in the wide range of 10°C to 50°C $T_a$. Gagge et al. (1967) mainly reported mean skin temperature ($\overline{T}_{sk}$) and focused on the prediction of thermal comfort (TC) and thermal sensation (TS). On the other hand, Werner and Reents (1980) observed a “sigmoid” relationship between $T_a$ and $T_{sk}$, with strong spatial variations towards the colder environments. In the 10°C environment, they noticed a 17°C difference between the toe and forehead after 90 minutes of rest in a minimally clothed condition.

Both groups of researchers combined the thermal load with a metabolic load on another series of experiments between 10°C and 48°C (Werner et al., 1985) and 10 and 30°C (Gagge et al., 1969). Looking specifically at individual $T_{sk}$, Werner et al. (1985) indicated that the temperature topography changed only to a small extent in exercising subjects and that the time constants for cooling of $T_{sk}$ are shorter at rest than at work.

Since these investigations (Gagge et al., 1967, 1969; Werner et al., 1980, 1985), the literature looking at various environmental conditions has paid more attention to cardiovascular and overall thermoregulatory responses ($\overline{T}_{sk}$ and $T_{core}$) during exercise (Adams et al., 1975; Maw et al., 1993; Galloway et al., 1997; Parkin et al., 1999; Sparks et al., 2005; Morante and Brotherhood, 2008) or to indoor comfort assessment (Tanabe and Kimura 1994; Yao et al., 2008). Minimal work has been done since on $T_{sk}$ patterns.

During exercise, the large majority of the literature has used cycling or running and only a limited body of literature is available at various ambient conditions regarding other exercise types such as upper-body exercise (Sawka et al., 1984; Pivarnik et al., 1988; Price and Campbell, 2002) or a combination of upper and lower-body exercise (Wells and Burskirk, 1972). In agreement with the experiments on lower-body exercise, $T_{sk}$ was related to $T_a$. Comparing upper and lower-body exercise in neutral and hot environment, it appeared that differences in $\overline{T}_{sk}$ were solely due to $T_a$ and the absolute metabolic intensity, not to the exercise type (Sawka et al., 1984; Pivarnik et al., 1988). Local $T_{sk}$ responses revealed that temperature over active muscles exceeds temperature over inactive muscles (Wells and Buskirk, 1973) with different local dry or evaporative heat exchanges depending on the exercise type (Sawka et al., 1984).
Rowing corresponds to a different exercise type which has been largely explored in the field of biomechanics (Hofmijster et al., 2008; Pollock et al., 2009), cardiovascular adaptations (Yoshiga and Higushi, 2002, 2003) or pacing strategies (Buckley et al., 2003, Lander et al., 2009). Only few studies reported thermoregulatory responses in rowing through $T_{core}$ and overall sweat rate (Slater et al., 2005; Maciejewski et al., 2007; Lander et al., 2009; Garrett et al., 2012). To our knowledge, $T_{sk}$ during rowing has only been measured on one occasion at four sites (Lander et al., 2009) showing no differences in the resulting $T_{sk}$ between a self-paced and constant pace rowing exercise with no reports of the regional $T_{sk}$. Regarding pacing, Lander et al. (2009) have demonstrated that a self-paced 5000m rowing was less challenging than a fixed power output trial (mean average of the self-paced trial) as indicated by lower lactate concentrations and lower muscles activities. Interestingly, the addition of 3 m.s$^{-1}$ air convection during rowing ergometry (50% $\dot{V}O_{2,max}$) in a 15°C environment led to reduced HR, RPE, oxygen uptake, sweat loss and $T_{re}$ compared to a still condition. The lack of knowledge on regional $T_{sk}$ in rowing ergometry as well as the interest of further understanding the impact of air temperature on thermoregulatory and perceptual responses justifies the choice of this exercise type for the present study.

The present study was therefore designed to explore the effect of AIR TEMPERATURE on the $T_{sk}$ distribution patterns during rowing ergometry. The protocol followed the same procedure as presented in Chapter 3 (running study). Additional analysis were also performed to compare the various semi-nude conditions investigated in the previous chapters (prolonged rest, lower-body exercise, full-body exercise) in order to assess the importance of EXERCISE TYPE on $T_{sk}$ distribution. It was hypothesized that:

1. Regional $T_{sk}$ will be lower and $T_{sk}$ variations across the body will be larger in the 10°C relative to the 20°C environment
2. $T_{sk}$ distribution will exhibit the same patterns in a 10°C or 20°C environment
3. The distribution patterns will highlight the activity-specific muscles involved in the rowing exercise with warmer skin overlying the active musculature. In both environments, regional heat production will however not prevent the drop in surface temperatures.
(4) The comparison of patterns using relative $T_{sk}$ body maps will demonstrate consistencies of core body regions and differences in limb regions due to the involvement of activity-dependent muscle masses.

5.2. Methods
Skin temperature mapping was performed on a group of eight physically active semi-nude males. All participants completed a pre-test session and two experimental sessions each separated by at least 48 hours. The experimental sessions were performed at the same time of day to prevent circadian effects, though different participants were tested at different times and therefore inter-individual variations in circadian thermal status was not controlled.

5.2.1. Participants
Eight males (non-specialist rowers) were recruited among the student population of Loughborough University with various exercise background (runners, footballers, rugbymen). They all signed an informed consent after explanation of the study methods and goals.

5.2.2. Pre-Test session
The pre-test session involved anthropometric measurements of height and body mass. Skinfold thickness measurements using a Harpenden caliper were also performed at 7 sites across the right side of the body for the calculation of body density (Jackson and Pollock, 1978) and then converted into % body fat using Siri’s equation (1956). The second part of the pre-test session consisted of a sub-maximal fitness test on the Concept 2 Rowing ergometer (model DPM3, Concept 2 Ltd, Wilford, UK). Drag factor was set at 120 as recommended by the manufacturer and used by others (Vogler et al., 2007). The sub-maximal test was designed following the guidelines of ACSM (2004) using a ramp test with 5*4min increments of 25 watts starting at 100W (1 min recovery between each stage). Maximal wattage was extrapolated using the linear relationship between heart rate and power output. Maximal aerobic power ($\dot{VO}_{2,\text{max}}$) was calculated based on calculations from Tikuisis et al. (1999) specifically based on rowing. After pilot studies, it was clear that non-specialist rowers could not sustain an intensity of 70% $\dot{VO}_{2,\text{max}}$ for 40 minutes due to localised
muscle fatigue in the arms. It was therefore decided to use a lower exercise intensity that would correspond to a specific RPE in order to match with the previous study using treadmill exercise (Chapter 3). The intensity was therefore set at $60\% \dot{V}O_{2\text{max}}$ as this was found to allow completion of the exercise bout and a RPE of 12 (“somewhat hard”).

Participants were familiarised with the subjective evaluation scales (thermal sensation, thermal comfort, RPE) during the first stages of the submaximal test. Scales corresponded to the one used for the generic skin temperature mapping protocol (cf 2.5).

5.2.3. Methodology

The experimental protocol (Figure 5.1) was following exactly the same chronology as presented in Chapter 3. Four different sets of infrared measurements were taken with the subject standing in an anatomical position: 5 minutes after entering the climatic chamber before rowing (PRE), after 10 minutes of rowing (ROW10), after 40 minutes of rowing (ROW40) and after 10 minutes of post-exercise recovery sitting on the rowing ergometer (POST10).

![Figure 5.1](image)

**Figure 5.1** Chronology of the study, Out in 22°C, 40% rh preparation room, Rest and Rowing in 10°C, 50% rh climatic chamber. Subjective and skin temperature mapping procedure at the different time point in **bold**

Participants wore only standardised swimming trunks (Tribord, Decathlon, Villeneuve d’Ascq, France), and their personal socks and shoes for the whole protocol. They were advised on fluid intake for maintenance of euhydration and to avoid alcoholic consumption and strenuous exercise within 24 hours prior to testing.
Figure 5.2 Picture of the experimental setting during the rowing phase in the climatic chamber

A vertical panel of three 50cm diameter fans (JS Humidifiers, Littlehampton, UK) was placed 10 cm away from the front of the rowing ergometer which corresponds to a distance of 75cm during the catch phase and 1.5m at the end of the stroke. Air velocity was coming from the front to reproduce the conditions in Chapter 3 though this was somewhat unnatural for the rowing activity where the posterior upper body is more exposed to relative air velocity. Our focus was clearly to match the conditions with Chapter 3.

All experiments were conducted in a controlled climatic chamber with two different environmental conditions in a balanced order: 10°C and 50% rh for the COLD trial and 20°C and 30% rh for the NEUTRAL trial. Relative humidity was adjusted in order to maintain the same evaporative cooling power between conditions using a psychometric chart (same water vapour content).

Heart rate (HR) was monitored using a Polar RS600 monitor (Polar Electro Oy, Kempele, Finland) The heart rate belt was worn over a 2-min period and then removed 5 minutes before each set of infrared measurements in order to avoid subsequent physiological (Tsk) and perceptual changes.

Infrared measurements were performed according to the procedure described in the skin temperature mapping protocol (cf 2.5) using the ThermaCam B2 (FLIR Systems Ltd, West Malling, Kent, UK).

Core temperature was monitored throughout the whole protocol using a rectal thermistor (Grant Instruments, Cambridge, UK) and recorded every 1 second using a data logger (1000 series Squirrel Eltek/Grant, Grant Instruments, Cambridge, UK).
Body mass and clothing mass were recorded upon arrival at the laboratory and immediately after the session using an electronic scale (Mettler Toledo kcc150, 150kg, Mettler Toledo, Leicester, UK). Body sweat loss was calculated from weight loss, adjusted for water intake and corrected for respiratory and metabolic mass losses.

5.2.4. Analysis

All infrared thermograms were processed using the custom-made MATLAB procedure in order to obtain group-averaged body maps at each phase of the protocol as well as quantitative $T_{sk}$ data for predefined regions (see Chapter 2). Relative body maps were also produced at each protocol stage and they reflected the body map relative to the group mean skin temperature ($\bar{T}_{sk}$) at each stage. The distribution of $T_{sk}$ above and below $\bar{T}_{sk}$ could then be compared with the thermal patterns obtained in previous chapters.

Mean skin temperature ($\bar{T}_{sk}$) was calculated as the average of all the pixels measured on the entire body surface by the 5 different thermograms taken of the participant at each time point, excluding the covered body parts (groin and feet). Statistical Analysis was conducted using the SPSS 16.0 (SPSS Inc, Chicago, IL, USA). A two-way repeated measures ANOVA was used to investigate the main effect of TIME and AIR TEMPERATURE. Dependent variables were $T_{re}$, $\bar{T}_{sk}$ and $T_{sk,local}$. Holm-Bonferroni corrections were applied to allow for multiple comparisons when comparing the different body regions investigated. A Pearson-correlation coefficient was obtained following regression analysis between $T_{sk}$ parameters (local or overall) and body fat parameters or perceptual parameters (local or overall).
5.3. Results

5.3.1. Participants

The participants’ characteristics, aerobic fitness level and the actual power output and predicted metabolic rate during both trials are presented in Table 5.1.

Table 5.1. Participants’ anthropometric characteristics (mean ± SD and range) and predicted aerobic fitness level for three distinct categories of body fat content

<table>
<thead>
<tr>
<th>Participant no</th>
<th>Body fat content (%)</th>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Body Mass (kg)</th>
<th>( A_{Du}/M ) (cm(^2)kg(^{-1}))</th>
<th>Predicted ( VO_{2,max} ) (mL min(^{-1})kg(^{-1}))</th>
<th>Absolute Power Output (W)</th>
<th>Absolute Metabolic rate (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>r1</td>
<td>12.4</td>
<td>21</td>
<td>173</td>
<td>64.7</td>
<td>273</td>
<td>44.6</td>
<td>107</td>
<td>594</td>
</tr>
<tr>
<td>r2</td>
<td>13.4</td>
<td>22</td>
<td>180</td>
<td>74.0</td>
<td>260</td>
<td>62.9</td>
<td>142</td>
<td>749</td>
</tr>
<tr>
<td>r3</td>
<td>10.7</td>
<td>22</td>
<td>181</td>
<td>75.4</td>
<td>258</td>
<td>54.6</td>
<td>124</td>
<td>670</td>
</tr>
<tr>
<td>r4</td>
<td>17.8</td>
<td>21</td>
<td>182</td>
<td>76.6</td>
<td>257</td>
<td>46.4</td>
<td>105</td>
<td>585</td>
</tr>
<tr>
<td>r5</td>
<td>13.1</td>
<td>22</td>
<td>180</td>
<td>85.2</td>
<td>240</td>
<td>51.1</td>
<td>132</td>
<td>705</td>
</tr>
<tr>
<td>r6</td>
<td>11.7</td>
<td>21</td>
<td>187</td>
<td>84.2</td>
<td>248</td>
<td>49.3</td>
<td>125</td>
<td>674</td>
</tr>
<tr>
<td>r7</td>
<td>18.6</td>
<td>22</td>
<td>175</td>
<td>81.2</td>
<td>242</td>
<td>46.7</td>
<td>113</td>
<td>621</td>
</tr>
<tr>
<td>r8</td>
<td>8.9</td>
<td>22</td>
<td>178</td>
<td>80.8</td>
<td>246</td>
<td>66.1</td>
<td>165</td>
<td>851</td>
</tr>
</tbody>
</table>

\( A_{Du} \) = body surface area; Mass = body mass; \( A_{Du}/M \) = body surface to mass ratio; \( V_{O_{2,max}} \) = predicted relative maximal oxygen uptake as calculated from Tikuisis et al. (1999) and ISO8996; Absolute Power Output at 60% \( V_{O_{2,max}} \) maintained during the trial; Predicted absolute metabolic rate at 60% \( V_{O_{2,max}} \) from Tikuisis et al. (1999).

5.3.2. Skinfold thickness

Skinfold thicknesses (SFT) measured at 7 locations are presented in Table 2.

Table 5.2. Participants’ skinfold thickness at 7 sites and sum of skinfolds

<table>
<thead>
<tr>
<th>Participant no</th>
<th>Chest (mm)</th>
<th>Triceps (mm)</th>
<th>Midaxillary (mm)</th>
<th>Subscapular (mm)</th>
<th>Suprailiac (mm)</th>
<th>Abdominal (mm)</th>
<th>Thigh (mm)</th>
<th>Sum of skinfolds (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>r1</td>
<td>8.8</td>
<td>8.8</td>
<td>10.0</td>
<td>15.5</td>
<td>15.3</td>
<td>17.0</td>
<td>17.0</td>
<td>92.3</td>
</tr>
<tr>
<td>r2</td>
<td>8.8</td>
<td>9.6</td>
<td>8.3</td>
<td>17.7</td>
<td>20.3</td>
<td>20.0</td>
<td>13.5</td>
<td>98.2</td>
</tr>
<tr>
<td>r3</td>
<td>7.4</td>
<td>7.8</td>
<td>7.7</td>
<td>11.8</td>
<td>13.3</td>
<td>14.4</td>
<td>17.6</td>
<td>80.0</td>
</tr>
<tr>
<td>r4</td>
<td>14.0</td>
<td>14</td>
<td>13.8</td>
<td>15.6</td>
<td>22.9</td>
<td>27.2</td>
<td>24.0</td>
<td>131.5</td>
</tr>
<tr>
<td>r5</td>
<td>11.1</td>
<td>12</td>
<td>10.0</td>
<td>14.5</td>
<td>19.6</td>
<td>14.0</td>
<td>15.4</td>
<td>96.6</td>
</tr>
<tr>
<td>r6</td>
<td>9.6</td>
<td>9.1</td>
<td>10.2</td>
<td>12.2</td>
<td>16.2</td>
<td>17.3</td>
<td>13.2</td>
<td>87.7</td>
</tr>
<tr>
<td>r7</td>
<td>8.6</td>
<td>16.8</td>
<td>19.4</td>
<td>21.5</td>
<td>21.3</td>
<td>24.8</td>
<td>24.9</td>
<td>137.3</td>
</tr>
</tbody>
</table>

\( \text{mean ± SD} \) range (6.0-14.0) (6.8-16.8) (6.3-19.4) (11.7-21.5) (12.8-22.9) (12.4-27.2) (12.1-24.9) (68.1-137.3)

5.3.3. Evolution of thermoregulatory parameters

This section introduces the main thermoregulatory responses induced by rowing at two \( T_a \). Similar dynamics were observed between the 10°C and 20°C condition for rectal temperature (\( T_{re} \)) but not for mean skin temperature (\( T_{sk} \)) as indicated by the significant interaction effect (TIME\*AIR TEMPERATURE, p<0.01). The difference in \( T_{sk} \) between conditions increased significantly with exposure time, being the
largest at ROW40 (4.8°C). There was no difference in $T_{re}$ between conditions as opposed to the significant $T_a$ effect on $T_{sk}$ ($p<0.001$) leading to an overall 4°C average difference between the 10°C and 20°C environment.

Sweat loss was significantly lower in the 10°C compared to the 20°C condition (111 ± 32g vs 232 ± 104g, $p<0.01$).

On top of the above thermoregulatory parameters, RPE was similar after 10 minutes of rowing (9.9 ± 1.5 vs 9.9 ± 1.1, NS) but it was significantly lower in the 10°C environment after 40 minutes of rowing (11.0 ± 1.1 vs 12.0 ± 1.2, $p<0.05$). This was consistent for all individuals. HR was similar between conditions (129 ± 6bpm at 10°C vs 131 ± 3bpm at 20°C, NS).

**5.3.4. Relationships between whole-body parameters**

**5.3.4.1. Mean skin temperature and overall body fat content**

A significant inverse relationship was found between $T_{sk}$ and %BF as well as sum of 7 skinfolds (same correlation coefficients) for the exercise and post-exercise stages in
the 10°C condition ($r = -0.86$ at ROW10 and ROW40, $p<0.01$; $r = -0.83$ at POST10, $p<0.05$) but not in the 20°C condition as shown in Figure 5.4.

![Figure 5.4: Mean skin temperature ($\overline{T_{sk}}$) in relation to body fat percentage (%) after 40 minutes of rowing (ROW40) at 60% $\dot{V}O_{2max}$ in a 10°C (●) and 20°C (○) environment](image)

**Figure 5.4**: Mean skin temperature ($\overline{T_{sk}}$) in relation to body fat percentage (%) after 40 minutes of rowing (ROW40) at 60% $\dot{V}O_{2max}$ in a 10°C (●) and 20°C (○) environment

### 5.3.4.2. Mean skin temperature and overall subjective votes

Overall thermal sensation ($TS_{overall}$) or overall thermal comfort ($TC_{overall}$) for individual participants was never correlated with $\overline{T_{sk}}$ at the four specific stages of the protocol.

### 5.3.5. Patterns of skin temperature distribution

The following figures (Figure 5.5, 5.6) provide quantitative data about the topography of skin temperatures in the two ambient conditions. The absolute $T_{sk}$ maps correspond to the arithmetic average of morphed thermograms of the 8 individuals (pixel by pixel) at each specific stage. The relative maps are obtained by dividing the matrix of the group absolute map by the group $\overline{T_{sk}}$ at that specific stage. This allows for a valid comparison between environmental conditions in terms of similarities or differences in the patterns as they are taking into account the body thermal state. Patterns of $T_{sk}$ distribution will be analysed in the discussion section.
Furthermore, the differences between the 10°C and 20°C condition in absolute and relative skin temperatures (relative to each group $T_{sk}$) are presented in Table 5.3 and local values (minimum, maximum) and $T_{sk}$ heterogeneity (maximal difference, variance) are given in Table 5.4.
**Figure 5.5**: Group-averaged maps of absolute (left panel) and relative (right panel) skin temperature at rest after 5 minutes sitting (PRE) and after 10 minutes of rowing at 60% $\dot{V}O_{2\text{max}}$ (ROW10) after morphing individual images of the 8 participants into a reference body shape. Relative = relative to each condition mean skin temperature (=1).
Figure 5.6: Group-averaged maps of absolute (left panel) and relative (right panel) skin temperature at rest after 40 minutes of rowing at 60% $\dot{V}O_2\text{max}$ (ROW40) and after 10 minutes of post-exercise recovery (POST10) after morphing individual images of the 8 participants into a reference body shape. Relative = relative to each condition mean skin temperature (=1).
Table 5.3: Significance levels of comparisons for ABSOLUTE and RELATIVE skin temperature between the two conditions (10°C vs 20°C) at all stages of the protocol (PRE, 10, 40, POST) for both uncorrected differences and Holm-Bonferroni corrected. Significant at p<0.05

<table>
<thead>
<tr>
<th></th>
<th>ANTERIOR BODY</th>
<th>POSTERIOR BODY</th>
<th>LATERAL BODY</th>
<th>PRE 10 40</th>
<th>POST 10 40</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 2 3 4 5</td>
<td>6 7 8 9 10 11 12</td>
<td>13 14 15 16</td>
<td>17 18 19 20</td>
<td>21 22 23 24 25 26</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.4: Minimum, maximum skin temperature (°C) for the anterior, posterior and lateral body with the corresponding regions name and number for the two environmental conditions at the four stages of the protocol. Group-average of the max-min skin temperature difference (°C) and group-average standard deviation over the whole body.

<table>
<thead>
<tr>
<th>Anterior Body</th>
<th>Posterior Body</th>
<th>Lateral Body</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIN (°C)</td>
<td>MAX (°C)</td>
<td>MIN (°C)</td>
<td>MAX (°C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRE 10°C</td>
<td>25.8</td>
<td>30.8</td>
<td>25.5</td>
</tr>
<tr>
<td></td>
<td>palm hands - 1</td>
<td>clavicular - 7</td>
<td>back hands - 17</td>
</tr>
<tr>
<td></td>
<td>29.1</td>
<td>32.9</td>
<td>30.4</td>
</tr>
<tr>
<td></td>
<td>patella - 15</td>
<td>clavicular - 7</td>
<td>hamstrings - 27</td>
</tr>
<tr>
<td>ROW10 10°C</td>
<td>21.3</td>
<td>26.8</td>
<td>21.8</td>
</tr>
<tr>
<td></td>
<td>patella - 15</td>
<td>volar elbow - 3</td>
<td>back hands - 17</td>
</tr>
<tr>
<td></td>
<td>26.6</td>
<td>30.3</td>
<td>27.3</td>
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<td>palm hands - 1</td>
<td>hps - 25</td>
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<tr>
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<td>23.6</td>
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<tr>
<td></td>
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<td>throat - 8</td>
<td>hps - 25</td>
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<tr>
<td></td>
<td>28.3</td>
<td>32.4</td>
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5.3.6. Local skin temperature and local subjective votes

The overall and local subjective votes (TS\textsubscript{local}, TS\textsubscript{overall}, TC\textsubscript{local}, TC\textsubscript{overall}) showed significant differences between T\textsubscript{a} conditions. The following figures demonstrate the magnitude of the perceptual differences associated with the T\textsubscript{sk} difference (between 10°C and 20°C) in large body segments.

**Figure 5.7**: Average overall and local thermal sensation for 8 non-specialist rowers at 60% \(\dot{V}O_{2\text{max}}\) in a 10°C (black) and 20°C (grey) environment associated with skin temperature difference (°C) between the two conditions before the exercise (PRE) and after 10 minutes of rowing (ROW10). The average sensation difference (Row at 20°C – Row at 10°C) is indicated in scale units at the bottom (e.g +6 for overall thermal sensation at ROW10). At PRE, 38% of the participants are in a state of thermal comfort at 10°C vs 100% at 20°C. At ROW10, 25% of the participants are in a state of thermal comfort at 10°C vs 88% at 20°C.
Figure 5.8: Average overall and local thermal sensation for 8 non-specialist rowers at 60% \( \dot{V}O_2\max \) in a 10°C (black) and 20°C (grey) environment associated with skin temperature difference (°C) between the two conditions after 40 minutes of rowing (ROW40) and after 10 minutes of post-exercise recovery (POST10). The average sensation difference (Row at 20°C – Row at 10°C) is indicated in scale units at the bottom (e.g. +3 for overall thermal sensation at POST10).

At ROW40, 63% of the participants are in a state of thermal comfort at 10°C vs 63% at 20°C.

At POST10, 75% of the participants are in a state of thermal comfort at 10°C vs 100% at 20°C.
The above figures highlight the regional sensitivities to $T_a$ in a rowing scenario on two different occasions. It was clear that extremities (hands and face) are not sensitive to strong $T_{sk}$ differences as opposed to the upper back with the highest sensitivity. In other words, a large change in $T_{sk}$ in the hands induced a small change in hand sensations with the opposite for the upper back.

Moreover, the cool to cold sensation prior to and at the start of exercise appeared to be detrimental for $T_{C_{overall}}$ in the 10°C environment as only 38% (PRE) and 25% (ROW10) of the 8 participants were in a state of thermal comfort.

On the other hand, at ROW40, the slightly cool (10°C) and slightly warm (20°C) $T_{S_{local}}$ were associated with the same 63% of comfortable participants. At that stage, regional $T_{sk}$ and $T_{re}$ were strongly different whilst $T_{re}$ was similar between $T_a$ conditions. Interestingly, RPE at ROW40 was significantly lower in the 10°C condition as indicated earlier.

In the two resting stages (PRE and POST10), the difference in $T_{S_{local}}$ between the environmental conditions was smaller (1 to 3 units) compared to the exercising stages (3 to 6 units). The difference in $T_{S_{local}}$ (between $T_a$) was not correlated with the $T_{sk}$ difference, reinforcing the concept of regional differences in thermal sensitivity.

Over the four stages, there was almost no significant correlation between subjective votes ($T_{S_{local}}, T_{C_{local}}, T_{S_{overall}}, T_{C_{overall}}$) and $T_{sk,local}$ as presented in table 5.5.

Using a between-regions approach, the distribution of local thermal votes ($T_{sk,local}$ and $T_{C_{local}}$) was analysed in relation to the distribution of $T_{sk,local}$ for 11 corresponding large regions. No significant correlations were found using this approach.

Overall, the local thermal votes ($T_{S_{local}}$ and $T_{C_{local}}$) that correlated the most throughout the protocol with overall thermal sensation ($T_{S_{overall}}$) and comfort ($T_{C_{overall}}$) were obtained at the anterior arms in the 10°C environment ($r = 0.82, p<0.01$). In the 20°C environment, it was the abdomen for $T_{S_{overall}}$ ($r = 0.89, p<0.01$) and the upper back for $T_{C_{overall}}$ ($r = 0.89, p<0.01$).
Table 5.6 Correlation coefficients table \((r\) values\) for the relationship between thermal votes at different body regions and local skin temperatures at all stages for the two environmental conditions \((n=32)\), during the exercising stages for the two environmental conditions \((n=16)\) and for all data combined at all stages \((n=64)\), and all data combined during the exercising stages \((n=32)\).

<table>
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<th>L.BACK</th>
<th>ARMS ant.</th>
<th>ARMS post.</th>
<th>LEGS ant.</th>
<th>LEGS post.</th>
<th>HANDS back</th>
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<td>TS overall</td>
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<td>0.00</td>
<td>-0.09</td>
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</table>

**Bold** values correspond to the best \(r\) values for overall votes. This corresponds to the significant correlations \((p<0.05)\).
In summary, the largest difference between $T_a$ for $T_{sk,local}$ and $TS_{local}$ occurred at the end of exercise which was on average +5°C warmer and +4 TS units higher respectively over the different regions in the 20°C compared to the 10°C environment. There was almost no correlation between $TS_{local}$ and $T_{sk,local}$ at specific stage or all stages considering a single $T_a$ condition. However, correlations were strongly significant when data from the two $T_a$ conditions were combined.

5.3.7. Local skin temperature and local skinfold thickness

The present study focused on 7 sites for skinfold thickness measurements with the associated $T_{sk}$ from the whole-body segmentation. It is worth mentioning that the range of body fat percentage or sum of skinfolds was larger than in the first study (see 3.2) about running (8.9-18.6% range = 9.7% vs 7.3-14.1% range = 6.8%).

| Table 5.6 | Correlation coefficients table (r values) for the relationship between local skin temperatures (°C) and local skinfold thickness (mm) of the different participants at 7 different body regions for the two environmental conditions and the four stages of the protocol |
|---|---|---|---|---|---|---|---|
| CHEST | TRICEPS | MIDAXILLARY | SUBSCAPULAR | SUPRAILIAC | ABDOMINAL | THIGH |
| PRE | 10°C | -0.44 | -0.83 | -0.28 | -0.70 | -0.60 | 0.01 | -0.25 |
| | 20°C | -0.51 | -0.06 | 0.12 | -0.23 | -0.69 | -0.17 | -0.50 |
| ROW10 | 10°C | -0.30 | -0.83 | -0.41 | -0.89 | -0.87 | 0.11 | -0.72 |
| | 20°C | -0.40 | -0.57 | 0.05 | -0.56 | -0.81 | 0.02 | -0.55 |
| ROW40 | 10°C | -0.21 | -0.80 | -0.50 | -0.82 | -0.77 | 0.02 | -0.74 |
| | 20°C | -0.22 | -0.65 | -0.06 | -0.75 | -0.68 | 0.25 | -0.18 |
| POST | 10°C | -0.01 | -0.77 | -0.60 | -0.92 | -0.64 | -0.11 | -0.76 |
| | 20°C | 0.06 | -0.43 | 0.14 | -0.77 | -0.65 | 0.22 | -0.28 |

Grey correspond to the significant correlations at p<0.05 and at p<0.01

There were only 3 significant correlations (out of 28 possible) in the 20°C environment at the subscapular site (ROW40, POST10) and the suprailiac site (ROW10). In the 10°C environment, there was a consistent negative relationship found at the triceps, subscapular and almost consistent at the suprailiac and thigh body sites.

5.3.8. Skin temperature distribution and environmental conditions:

The present study allows the comparison of thermoregulatory and perceptual responses in a 10°C and 20°C environment. This can also be done for the spatial variation in $T_{sk}$ through the group-averaged relative body maps (Figure 5.6) with the
production of a relative $T_{sk}$ difference body map (Figure 5.9). The latter displays the
topography of regions that respond differently in the two $T_a$ conditions.

![Figure 5.9: Anterior and posterior maps of relative skin temperature difference between the 10°C and 20°C conditions after 40 minutes of rowing (ROW40 at 20°C – ROW40 at 10°C). Dimensionless unit (subtraction of dimensionless relative $T_{sk}$ values).](image)

According to Figure 5.6, Table 5.3 and Figure 5.9, slight temperature distribution differences (within -0.15 and 0.15) could be observed specifically in the upper back and anterior legs although participants were exercising at the same workload in both $T_a$ conditions. Cautious interpretation is required as the range of skin temperatures between regions was larger in the 10°C environment.

**5.3.9. Skin temperature distribution and exercise types:**

The three main studies presented so far (Chapter 3,4,5) involved various conditions with prolonged rest and different exercise types. Although they were based on different groups varying in body fat percentage or physical fitness levels, they all had in common the same environmental conditions (10°C, 50% rh) and participants exposed in a minimally-clothed condition (swimming trunks). Moreover, it was possible to specifically observe the thermal patterns at similar time of exposure (45-55 minutes). Figure 5.10 summarises the group-averaged relative body maps for these different exposures in similar environmental and clothing conditions.
It can be observed that body regions located close to the “core” remained warmer for all exercise types (sternal, supraclavicular, face regions) with a large variety of response in the limbs depending on the type of activity.

![Figure 5.10](image)

**Figure 5.10** : Relative body maps of skin temperature after 40 minutes of running at $70\% \dot{VO}_{2,\text{max}}$ (RUN), after 40 minutes of rowing at $60\% \dot{VO}_{2,\text{max}}$ (ROW), after 30 minutes of cycling at 100W (CYCLE) and after 55 minutes of seated rest (REST), all in a 10°C 50% environment minimally clothed. Mean body fat percentage varied for the different groups (9.5±2.4% RUN, 13.3±3.3% ROW, 12.6±1.6% CYCLE and REST).

Regarding Figure 5.10, it is also important to note that frontal relative air velocity was absent for the resting and cycling conditions as opposed to running and rowing (where $v = 2.8\text{m.s}^{-1}$).

The rowing and running study were based on an identical protocol, however the workload could not be similar because participants were non specialist rowers and could not sustained a power output corresponding to $70\% \dot{VO}_{2,\text{max}}$ due to localised fatigue over 40 minutes. As a consequence of the differing metabolic rates, $T_{\text{re}}$ increased only by 0.52°C during rowing compared to 1.0°C during running. Interestingly, there were no significant differences in the $T_{\text{sk}}$ values and the
dynamics was also similar between running and rowing. Despite similar $\bar{T}_{sk}$, the $T_{sk}$ distribution was strongly different between the exercise types. The following figure 5.11 visually highlights the spatial differences in relative temperatures by a substraction of the group-averaged relative maps presented in Figure 5.10. It becomes apparent that the warmer anterior arms and abdominal regions are specific to rowing exercise whereas the warmer lower legs and hamstrings are more associated with running.

![Figure 5.11: Anterior and posterior maps of relative skin temperature difference between running at 70% $VO_2_{\text{max}}$ and rowing at 60% $VO_2_{\text{max}}$ in a 10°C environment, minimally clothed after 40 minutes of exercise (RUN-ROW). Dimensionless unit (substraction of dimensionless relative $T_{sk}$ values).](image)

Although based on two separate groups of participants, the analysis revealed that differences in perceptual responses were very limited despite different $T_{sk}$ distribution, different rise in $T_{re}$ but the same $\bar{T}_{sk}$.

The anterior arms and abdominal regions were on average 2.0°C (absolute $T_{sk}$) warmer for the rowers compared to the runners during the exercising stage with similar thermal sensation or comfort votes. Similarly, the posterior legs reached values 2.3°C warmer on average for runners at the end of exercise with no differences in perceptual votes. The only obvious difference was observed for the dorsal hands after 10 minutes of exercise, with 3.2°C colder $T_{sk}$ during running perceived as *cold* compared to *cool* during rowing (2 units on the thermal sensation scale, see 2.4.9), leading to a large discomfort for runners. Even in a semi-nude
condition at 10°C, cold sensations only occurred for part of the groups (~65%) after the initiation of exercise and yet no more than 50% of participants reached a state of discomfort throughout the whole protocol. Some limitations, mentioned above, prevent from a strict comparison to be performed but the data are valuable for observation.

In summary, each exercise type displayed a specific $T_{sk}$ distribution. It was clear that frontal air velocity had a strong influence on the anterior body. Despite these differences, several consistencies in thermal patterns could be recognized and will be discussed. The comparison of running and rowing in similar cold conditions would suggest that different $T_{sk}$ distribution but same $\bar{T}_{sk}$ induce similar perceptual responses.

5.4. Discussion

The aim of the present study was to explore the role of an external determinant of $T_{sk}$ (AIR TEMPERATURE). Furthermore, the study was also performed in the same ambient conditions (10°C) to previous experiments involving different exercise types or prolonged rest. With some limitations, the comparison of these different conditions was relevant in order to further understand $T_{sk}$ distribution.

The main findings can be summarised:

- Larger variations in $T_{sk}$ over the body were observed at 10°C compared to the 20°C environment, with the expected lower regional $T_{sk}$ and $\bar{T}_{sk}$ (~ 4°C overall).
- Perceptual differences were significant with some regional specificities, i.e, the same difference in regional $T_{sk}$ did not result in a similar change in perception depending on the body regions.
- The distribution of $T_{sk}$ was relatively similar during rest and exercise in both ambient conditions but some slight differences were highlighted in the thermal patterns at 10°C and 20°C.
- Additional evidence of warmer skin overlying activity-specific muscles was provided with the rowing thermal patterns.
- The observations of all the relative patterns underlined the core body regions and the dynamic vasomotor adjustments in the limbs depending on the body condition (prolonged rest, lower-body exercise, full-body exercise).

5.4.1. The influence of air temperature on thermoregulatory parameters

Thermoregulatory responses were differently affected by $T_a$. No differences were reported in $T_{re}$ which is in line with the classical observation from Nielsen (1938) and Saltin and Hermansen (1966) indicating that $T_{core}$ during exercise levels off at a value directly related to metabolism and independent of environmental temperature between 5 and 30°C.

On the other hand, $T_{sk}$ during exercise was directly related to ambient conditions (10 vs 20°C) as previously observed (Werner et al., 1985) and it has been shown that it is relatively independent of the workload performed (Gagge et al., 1969).

$T_{sk}$ during a rowing exercise was recorded in one earlier study (Lander et al., 2009) which consisted of a submaximal 5000m trial at a fixed RPE (15 “hard”) and fixed power output (equivalent to the mean power output of the RPE condition). In a 18°C environment, $T_{sk}$ increased by 1.7°C on average in both trials lasting 18 minutes (30.6 at t0 and 32.3 at t18). This contrasts with our finding of a decreased $T_{sk}$ at T10 and T40 compared to pre-exercise values by approximately 3°C in the 20°C condition. The absence of air velocity in their protocol (Lander et al., 2009) may partly explain this discrepancy.

Only few studies have explored the $T_{sk}$ responses in 10°C vs 20°C condition, and exclusively using contact measurements. Galloway and Maughan (1997) found a 5°C difference in $T_{sk}$ after 40 minutes of cycling at 70% $\dot{VO}_{2\text{max}}$ in an 11 vs 21°C environment which is similar to our study (4.8 ± 0.8°C between 10 vs 20°C) despite their lower air velocity (0.7 m.s$^{-1}$ vs 2.8 m.s$^{-1}$). The difference after 10 minutes was however slightly lower than ours (3°C vs 4°C). It can be suggested that the cooling power of the wind in association with low ambient temperatures favoured a rapid fall of $T_{sk}$ early in exercise (within the first 10 minutes). The increase of $T_{sk}$ difference between $T_a$ throughout the exercise can be interpreted as an absence of stabilisation in the cold environment whereas heat balance had been reached in the moderate condition.
With no relative air velocity, Gagge et al. (1969) reported approximately a 2°C difference at 50 and 75% \( \dot{V}O_{2\text{max}} \) between 10°C vs 20°C conditions after 40 minutes of cycling. Ten males exhibited a 4°C lower \( T_{sk} \) consistently throughout a duathlon (running + cycling + running) in a laboratory at 10°C vs 20°C (front air velocity 1.3 m.s\(^{-1}\))(Sparks et al., 2005). Overall, exercise modes and experimental conditions varied greatly so that a valid comparison is not conceivable. This however emphasizes the large importance of wind speed in the determination of \( T_{sk} \), which has been modelled during cold exposure at rest (Iampietro 1961).

Similarly to our results, sweat loss was found to be significantly lower in the 10°C environment in all afore mentioned studies and this highlights the larger contribution of evaporative cooling during exercise in moderate to warm environments. In other words, heat balance can be maintained through larger dry heat exchanges at 10°C induced by the important air to skin (\( T_a - T_{sk} \)) gradient.

Lastly, the significant relationship between \( T_{sk} \) and \%BF/sum of skinfolds at 10°C but not at 20°C (Figure 5.4) demonstrates that body fat becomes a crucial factor at low air temperatures. This contrasts with the result from chapter 3 with a group of male running in a 10°C showing no significant association. This absence of correlation may however be explained by the smaller range of body fat (7-14%BF for running study vs 9-19%BF for rowing study) however. On the other hand, this significant correlation was in agreement with the results of resting and exercising males (Chapter 4) where the body fat range was the largest (7-40%BF).

- Air temperature did not significantly influence the \( T_{re} \) response throughout the exercise at the same absolute workload. However, \( T_a \) induced lower sweat loss and lower \( T_{sk} \) in the cold environment. A 10°C air temperature difference in the presence of 2.8m.s\(^{-1}\) wind led to a 4°C \( T_{sk} \) difference on average over the whole protocol. The conditions in the 10°C were highly favourable for a larger radiative and convective cooling (dry heat transfer), requiring lower evaporative cooling.

5.4.2. The influence of air temperature on skin temperature distribution

The \( T_{sk} \) variance between body regions was larger in the 10°C compared to the 20°C environment, which is in line with many reports looking at various \( T_a \) at rest (Vegthe,
1965, Werner et al., 1980; Livingstone et al., 1987; Pascoe et al., 2001) and during exercise (Clark et al., 1977; Werner et al., 1985)

The difference between the minimum and maximum $T_{sk}$ across the body after 40 minutes of rowing was 8.4°C and 6.0°C at 10°C and 20°C environment respectively. In similar environments, a 10°C difference between foot and forehead after 75 minutes of cycling at 40% $\dot{V}O_{2\text{, max}}$ was observed in one subject (Werner et al., 1985).

In their study, $T_{sk}$ measurements were obtained from 13 thermistors and may not reflect the real extreme regions.

In our study, it was interesting to observe that the extreme regions remained consistent throughout the protocol with the patella being the coldest and the upper back the warmest region in both environments (Table 5.4). This echoes the first thermographic assessment in various environments, though this was done at rest in 4°C, 23°C, 27°C (Veghte, 1965). He found consistencies in the regions with extreme temperatures, the lower leg being the coldest and the sternal region being the warmest, followed by the upper back.

In our data, the cold upper extremities (dorsal and palmar hands) in the 10°C conditions at PRE and ROW10 highlights the role of the vasoconstrictor tone which controls blood flow in the hands (Kellogg et al., 1991). The release of this tone only occurred after more than 10 minutes of rowing.

Regional $T_{sk}$ distribution was highlighted in our study via the population-average relative $T_{sk}$ body maps (Fig. 5.5, 5.6) and the body map of relative $T_{sk}$ difference (Fig. 5.9). Many similarities could be observed between $T_a$ conditions with some consistent features such as the Y-shape of colder $T_{sk}$ over the anterior torso, which was limited to the colder pectoral during rest and recovery.

The large majority of warmer $T_{sk}$ were found in the upper torso as opposed to the colder lower limbs, especially in the active arms and upper back muscles. This will be discussed in more depth in 4.4. The concept of normalised relative maps is important but should be viewed with caution in this precise case where variance in $T_{sk}$ was larger in the 10°C compared to the 20°C condition.

Similarities in $T_{sk}$ patterns between 10°C and 20°C environments have also been reported before and during running (Clark et al., 1977) or during cycling (Torii et al., 1992), both using infrared thermography. These interpretations were however limited to the observation of only one individual and they were not supported by a
quantitative and qualitative assessment such as our normalised $T_{sk}$ values and body maps.

From Werner’s topography of $T_{sk}$ using 13 thermistors (Werner et al., 1985), it can be extrapolated that $T_{sk}$ distribution would remain quite similar at 10°C and 20°C after 75 minutes of cycling at 40% $VO_{2,max}$ except for the calf becoming the second coldest region.

Although the role of wind speed was not explored in the present study, Clark et al. (1977) indicated that air velocity (16km.h$^{-1}$) reduced absolute $T_{sk}$ by 4°C (compared to still air) but did not impact the $T_{sk}$ distribution for one male running at 16 km.h$^{-1}$ in a 10°C environment.

- Our data support the notion that AIR TEMPERATURE only little affects the $T_{sk}$ distribution patterns. It is yet obvious that the $T_{sk}$ variance became much larger in the cold environment, with $T_{sk}$ difference across the body (warmest – coldest regions) of 8.4°C and 6°C at 10°C and 20°C respectively.

5.4.3. The influence of air temperature on perceptual responses

The impact of $T_a$ can be quantified regarding temperature sensations, comfort and effort perceptions.

A change of 1 category units for TS$_{overall}$ was caused by a change of 2°C in $T_{sk}$ which is in line with results from Gagge et al. (1969) based on 4 exercising subjects and 72 series of experiments (at 10°C, 20°C, 30°C). The same increase in sensation was caused by a change of 5°C in $T_a$, slightly lower than 7°C found by Gagge et al. (1969) and most likely due to the presence of air velocity in our protocol. It is important to note that this slope calculation ($\Delta T_a / \Delta TS$) is only based on two $T_a$ conditions in our case as opposed to three in Gagge’s study.

Regional differences were observed for thermal sensitivities ranging from highly tolerant hands and the most intolerant region being in the upper back, with moderate values for all the remaining regions. A change of 1.8°C $T_{sk}$ was sufficient to provoke a change of 1 category unit in the upper back whereas this occurred for 5.5°C $T_{sk}$ change in the hands. In our conditions, the $T_{sk}$ difference over the whole-body was passively induced by the 10°C difference in $T_a$, other parameters being kept equal (clothing, metabolic rate).
This passive and natural exposure is difficult to compare with the active and local intervention (by conduction with Peltier plate) proposed in sensitivity studies, cooling or warming small segments during moderate exercise (Ouzzahra et al., 2012) or large regions at rest (Crawshaw et al., 1975; Stevens 1979; Nakamura et al. 2008, 2013).

Regarding the perception of TC, it was clear that more participants experienced slight discomfort in the 10°C compared to the 20°C environment during the first two phases of the protocol (PRE and ROW10, see Fig. 5.7). Participants had a similar T_re but a 4°C lower T_sk as well as a faster drop in T_sk (first 10 minutes of exercise) in the 10°C environment which may have caused this discrepancy. Slight discomfort was perceived locally especially in the anterior arms and the face with cool thermal sensations. However, as time of exercise progressed together with T_re, it was interesting to observe that 6 out 8 participants were in a state of thermal comfort in both environments after 40 minutes of steady state exercise at the same intensity. This was obtained with similar T_re values but lowered T_sk in the 10°C condition and temperature sensations in the slightly cool range (10°C) as opposed to slightly warm range (20°C). An individual analysis of results highlights that the 2 uncomfortable participants at 10°C (r1 and r2) were still experiencing an overall cool sensation and the 2 uncomfortable participants at 20°C (r1 and r3) in the hot environment were in a state of warm discomfort due to sweating as also described by Gagge et al. (1969).

Additionally to differences in thermal perceptions, a significant difference of 1 unit (11.0 vs 12.0) on the RPE scale was observed between the two environmental conditions. HR was not different between the two conditions. The exercise was perceived less strenuous in the cold environment. This finding is in line with the only few studies that have examined the effects of neutral vs cool to cold environments on psychophysical and physiological responses during exercise (Nelson et al., 1991; Maw et al.,1993). Maw et al. (1993) suggested that RPE was most sensitive to peripheral inputs ($T_{sk}$) than central factor (T_re). Moreover, afferences from skin thermoreceptors must be crucial at the onset of exercise in pre-setting the brain conscious response towards a protection of whole-body homeostasis during prolonged exercise (avoiding dangerous hyperthermia) (Crewe et al., 2008) which agrees with the model of teleo-anticipation (Ulmer 1996).
Overall, we observed that a reduced thermal load (lower $T_a$) represents an interesting way to reduce $T_{sk}$ and consequently modify the generation of conscious behavioural response towards a less strenuous exercise. Many studies in the literature (Young et al., 1987; Minniti et al., 2011; Wegmann et al., 2012) have used cooling interventions which have demonstrated the crucial role of $T_{sk}$ and the benefits of colder afferences to the brain, in some cases alleviating heat strain, improving performance, or increasing the pleasantness of the exercise which is a key for mass participation.

For a general audience, it seems important to encourage participation even in low $T_a$ by providing the necessary adjustments (thermal protection) during the immediate exposure and onset of exercise that might be unpleasant. For the remaining part of the exercise, they will however benefit from lower $T_{sk}$ induced by the enhanced heat exchanges of the cold environment compared to the neutral or warm environment.

Air temperature significantly influenced TS and this was associated with much lower $T_{sk}$ across the body at low $T_a$. However, there was only minimal discomfort among subjects considering sensations remained between *slightly cool* and *slightly warm*. $T_{sk}$ seems to play an important role both for sensation and for the perceived exertion which was lower in the cold environment, $T_{core}$ being similar between $T_a$ conditions.

### 5.4.4. Differences between exercise types

Our results provide additional evidence of the importance of active muscles in the $T_{sk}$ distribution patterns regardless of $T_a$. This confirms the findings of Veghte et al. (1979) and Clark et al. (1977) both on only one subject, reporting a 2-4°C warmer skin over active muscles compared to adjacent areas. In our population of rowers, the active biceps were 1.5°C warmer than the adjacent shoulder region in both environments. It can be assumed that a “direct vascular convection of heat” radially from active muscle to overlying skin via venous blood flow takes place as suggested by Cooper et al. (1959) with blood circulating from deep to superficial veins as shown by Gisolfi and Robinson (1970) during treadmill exercise. The role of perforator veins has also been discussed by Merla et al. (2010) and precisely observed by Binzoni et al. (2004). In our thermograms, the appearance of perforators was more pronounced during the recovery phase when the thermoregulatory system takes up a leading role to dissipate heat in contrast with the metabolic demand during
exercise. Considering the high spatial inter-individual variability of the hot spots due to perforator veins, they can be more readily observed on individual thermograms (Merla et al., 2005, 2010).

In Chapter 3, 4 and 5, the exploration of different exercising and resting situations in combination with cold exposure also highlighted the activity-specific muscles involved in these activities.

Figure 5.10 summarises thermal patterns in a 10°C environment for various conditions. Lower-body muscles contribute primarily in lower-body exercise with specifically the lower leg (calves) during running (weight-bearing exercise) and the upper leg during cycling (non-weight bearing exercise). On the other hand, upper body muscles were clearly warmer than the surrounding tissues during rowing especially the anterior arms (most importantly the biceps) and upper back (trapezius).

In the framework of our study, the thermal patterns revealed that lower body muscles were insufficiently active during the rowing trial to create a thermal signature. This was indirect evidence that our participants were non-specialist rowers insofar as more elite rowers predominantly use back as well as quadriceps muscles (Raymond et al., 2007). During the rowing motion (catch, drive, finish, recovery), it can be speculated that non-specialist rowers may anticipate the arm pull within the body swing in the drive phase, which accentuates the workload imposed on the arms muscles.

The infrared body maps of rowing participants are the first to document the influence of full-body exercise in air on $T_{sk}$ distribution for a large population. Infrared image of one participant was obtained for arm and leg cranking exercise in Clark and Edholm (1985).

![Figure removed due to copyright](image)

**Figure 5.12** Illustration of arm and leg cranking exercise (from Clark and Edholm, 1985)

Contact measurements were performed in a similar experimental setting, though with only contralateral limbs exercise (Wells and Buskirk, 1972). The data support the
redistribution of blood flow induced by exercise with $T_{sk}$ of active limbs exceeding those of contralateral inactive limbs. Moreover, they discussed the difference between arms and legs anthropometry (geometry, mass, muscle type, partitional blood flow). The high arm temperature values suggested that a greater amount of metabolic heat per unit of muscle mass may be produced compared to the legs. This could also be due to the larger fat thickness, the larger volume, the lower surface area-to-mass ratio in the legs (Wells and Buskirk, 1972).

*Full-body exercise* in water had already been explored with the infrared body maps of 4 males after swimming produced by Wade and Veghte (1977). They also highlighted the importance of active muscles in the upper body (deltoid, trapezius, pectorals) and lower body (sartorius involved during kicking). The distribution of $T_{sk}$ was independent of skinfold thickness which is in agreement with our data on running, cycling or rowing in air.

A preliminary experimental study (Zaidi *et al.*, 2007) has provided some insights into the influence of swimming style on $T_{sk}$ distribution, with the observation that back stroke overall $\bar{T}_{sk}$ was the highest (based on one individual). The authors hypothesized that this style was the most demanding but this may well be the influence of posture and the less efficient convective cooling of the water on the anterior body due to the depth of the body in back stroke.
Another exercise type commonly used in research is hand grip exercise. Veghte et al. (1979) observed that the Tsk rise in upper and low medial regions of the forearm was proportional to the increase in percentage of maximal muscular effort. However, hand gripping also resulted in cooling of fingers which were deemed to be due to the progressive compression of the palmar arch artery (Veghte et al., 1979). The comparison of all exercise types emphasizes the distinct definition of core body regions which consistently remain warmer than other regions. The core body regions are found in the neck and upper back as well as in the sternal regions (Figure 5.10, 5.12, 5.14). In contrast with this similarity, each exercise type induces a specific redistribution that can be predicted from the active musculature involved in the exercise. This redistribution is assumed to be in large part due to blood flow redistribution in connection with the specific metabolic demand of active muscles. As indicated by Veghte (1965), the area and temperature of the localised radiators (warm areas) would depend on the activity, the posture and Tcore of the subject. In our rowing experiment, it is important to consider the seated posture which was different from the running or cycling posture. The difference in posture modifies the surface area available for heat exchange. Kabayashi et al. (1980) were one of the first to investigate this factor during rest and exercise in extremely hot environment (50°C). They observed higher Tre and Tsk for the supine posture associated with lower evaporative heat loss, compared to low-sit and upright postures. Tikuisis and Ducharme (1996) observed similar Tsk but higher Tre for the standing compared to the seated posture in a 28°C air environment at rest.
The rowing posture is relatively complex throughout the different stroke phases. There are constant temporal variations in the total surface area exposed to the frontal air velocity (2.8 m.s\(^{-1}\) in our study), with the quadriceps and posterior legs being the least exposed. On the other hand, the posterior upper body was not exposed to forced convection but was still experiencing an assumed important convective cooling due to the displacement of the ergometer seat. It was also clear that the abdominal region was made artificially warmer due to the conduction between abdominal tissues in contact during the seated posture.

- The present thermographic data document for the first time \(T_{sk}\) distribution for a full-body exercise across a large population. They provide additional evidence that activity-specific muscles are warmer than the surrounding tissues together with the consistent core body regions regardless of the exercise type or \(T_a\). It is suggested that IR thermography may also be helpful to observe differences in muscle recruitments between groups with various technical expertise but this point requires further investigation. The influence of the body posture has been discussed as it may not be negligible in explaining local \(T_{sk}\).

5.5. Conclusions

The findings of the present study are mainly focused on the comparison between the same exercise (same workload) performed at two different environmental conditions. They can be summarised as below:

- **Air temperature** did not significantly influenced \(T_{re}\) at the same absolute workload but induced lower sweat loss and lower \(T_{sk}\) in the cold environment. A 10°C air temperature difference in the presence of 2.8m.s\(^{-1}\) air velocity led to a 4°C \(T_{sk}\) difference on average over the whole protocol. The difference was greater with exercise duration due to a lack of stabilisation in the cool environment

- **Air temperature** only little affects the \(T_{sk}\) patterns. However, \(T_{sk}\) non-uniformity became much larger in the cold environment, with \(T_{sk}\) difference
across the body (warmest – coldest regions) of 8.4°C and 6°C at 10°C and 20°C respectively. Some active regions during rowing seemed to behave differently in the two environments and further investigation would be required to explore this phenomenon.

- **Air temperature** significantly influenced thermal sensation in association with much lower $T_{sk}$ across the body. However, there was only minimal discomfort among subjects considering sensations remained within the range of *slightly cool* to *slightly warm*. $T_{sk}$ seems to play an important role both for sensation and for the perceived exertion which was lower in the cold environment, $T_{core}$ being similar between conditions.

Moreover, it was judged interesting to observe thermal patterns from all results so far obtained in a similar $T_a$ (10°C) clothing (swim trunk), sex (males) and time of exposure (45-55min). Although strict comparisons are not possible mainly due to differences in population (body fat, fitness level) and metabolic rates, it gives a good representation of what can be expected when different exercise types are performed. The main conclusion was:

- The present thermographic data document for the first time $T_{sk}$ distribution for a *full-body exercise* across a large population. Despite similarities observed in the core body regions, IR thermography can highlight the activity-specific muscles for different types of exercise or $T_a$. 

CHAPTER 6

Evaluation of the thermal strain induced by a simulated hill walk: sex differences and the effect of wearing a backpack

Chapter Summary

In this chapter, skin temperature variations under clothing were examined, taking recreational hiking as an illustration of a popular activity with potential large variations in climate and terrain. A group of 8 males and 8 females performed a walking scenario with a backpack (10% body mass) over 105 minutes with a resting period exposed to the wind between the uphill and downhill phases. Regional skin temperatures were lower for females only in the upper and lower limbs with mean skin temperature being 0.6°C lower for females. Skin temperature distribution was similar between sexes. Females reported more cold discomfort before hiking and during the wind exposure. Moreover, the group of males performed the same scenario without a backpack (same relative workload). Wearing a backpack induced an overall 0.6°C warmer mean skin temperature compared to no backpack and local differences as large as 3°C warmer temperatures over the lower back with backpack. Thermal and wetness sensations reached high levels sooner during the ascent with backpack but were similar between conditions at the end of the ascent and for the remaining stages.

Context

The previous chapters have explored thermoregulatory and perceptual responses of males and females in semi-nude conditions in different contexts. The main focus was to understand the role of internal determinants (regional fat thickness, regional muscle heat production) on the $T_{sk}$ patterns and the associated subjective thermal responses. Air temperature has been the only external determinants studied so far. An important external factor that has been the key for human survival in cold environments throughout evolution is CLOTHING with necessary adaptation depending on the severity of the environment. Clothing adjustments in order to
maintain thermal balance correspond to one of the most effective ways of thermoregulation called behavioural thermoregulation. The influence of clothing is therefore an important external determinant to investigate in the evaluation of human activity, due to its important contribution to our everyday life for both social and thermal requirements.

Clothing comfort represents a complex multi-sensorial concept that depends upon various perceptions of comfort (Li, 2001). The four determinants of clothing comfort are tactile comfort (when touching or wearing), psychological comfort (related to aesthetic appeal in close connection with the socio-cultural importance of clothing), garment fit comfort (related to the freedom of movement), and thermophysiological comfort. Whilst the first two perceptions rely upon an almost instantaneous observation, garment fit and thermophysiological comfort are dynamically modified depending on the human activity. It is worth noting that garment fit through sizing is inter-connected with thermophysiological comfort as changes in air layer around the body will influence the heat and vapour transfer properties through clothing, in turn modifying thermal perceptions.

The following chapters (Chapter 6 and 7) will explore the role of clothing on thermophysiological perceptions with a special interest in the concurrent thermal changes occurring within the human body. Firstly in Chapter 6, the mapping methodology from the previous chapters will be applied to a laboratory-based protocol for the observation of the specific hill walking activity. This can have direct practical relevance for mountaineering sport products. Secondly in Chapter 7, an intervention will be performed on runners via modification of the clothing insulation distribution and its associated impact on overall and regional thermoregulatory as well perceptual responses.

6.1. Introduction

Hiking is an increasingly popular recreational activity with large participant numbers who vary widely in terms of age, gender and hiking experience (Simpson, 2011). Hikes can range from single day to multi-day expeditions. Load carriage is very often associated with hill walking and varies depending on the type and duration of the hike. It has been extensively studied as it is a key aspect for military personnel (Patton et al., 1991). Load carriage can also lead to discomfort (Gordon et al., 1983)
and sometimes to musculoskeletal injuries such as paresthesia (compression of a peripheral nerve) during very prolonged events (Anderson et al., 2009).

During a recreational day walk, hikers usually carry the minimum amount of food and equipment in their backpacks so that the experience can be completely enjoyable and minimally affected by pain and discomfort from load carriage. The weather becomes the critical aspect of the event and the selection of the correct clothing ensemble is crucial for hiking. Back in the 1960’s, Pugh launched important field research in order to understand the mechanisms that were involved in the deaths of two adolescents in the “Four Inns Walk” in Derbyshire in 1964. With his important contribution and some of more recent research groups (Ainslie and Reilly, 2003; Young and Castellani, 2007), they came to the conclusion that hikers’ hypothermia was mainly induced by reduced clothing insulation (in cold, wet and windy weather) and progressive fatigue due to sustained physical exertion (inability to compensate heat loss with heat production). This raised awareness to the important role of adequate clothing (water repellent, minimal condensation) and good adjustment in energy expenditure. Groups or families walking at the same pace may represent an important risk to the less fit individuals, having a larger workload relative to their fitness level and therefore more exposed to fatigue. Overheating with inadequate clothing can turn into a danger of hypothermia at the cessation of exercise or in reduced intensity due to fatigue and potential dehydration (Ainslie and Reilly, 2003). Dehydration has been found to be more pronounced in a group of elderly and it led to reduced cognitive performance after strenuous hill walking (Ainslie et al., 2002).

Most of the literature on the thermal strain of hill walking has either examined the metabolic or thermoregulatory responses over prolonged events with field tests (Ainslie et al., 2005) and intense day walks with adverse environments in laboratory-based studies (Weller et al., 1997). Impressive laboratory settings have even been built for some exploration with controlled conditions for wind and constant wetting (Thompson et al., 1996). However, none of the studies described the strain faced by recreational hikers in fairly good but cold conditions for a simple day-hike. The vast majority of moderately experienced hikers do not undertake day hikes in adverse environments. Moreover, experienced hikers could accept more difficult weather conditions but they may still experience thermal discomfort during the event. Our aim was to offer a descriptive approach of the thermal strain during a day-hike by
simulating non-adverse outdoor conditions, various terrains and clothing adjustments in the laboratory.

Pugh (1969) stated that in outdoor activities man regulates his own $T_{sk}$ by adjusting his clothing and he found that the range of mean skin temperature preferred by walkers was 29°C to 31°C. He also noted the opposing changes in $T_{re}$ and $T_{sk}$ during exercise such that mean body temperature remained virtually unchanged at rest and during exercise so long as the subjects were in a state of thermal comfort. During a field experiment in autumn and winter, he observed that some individuals complained of cold due to low regional $T_{sk}$ despite little change in mean body temperature. To our knowledge, no other study has paid attention to a hiker’s thermal comfort and discomfort, especially in cold conditions.

The present study was therefore designed to simulate a day-hike (ascent, summit break, descent) in a condensed manner (110 minutes) with the potential discomfort imposed by cold exposure at rest, excessive sweating during the ascent, followed by the cold after-chill experienced in windy open areas. The mapping methodology was particularly relevant in order to associate regional subjective response together with the main thermoregulatory responses, especially regional $T_{sk}$. The effect of SEX was explored with a population of young males and females. Moreover, the effect of wearing a BACKPACK was included in the protocol to understand the relative contribution to regional discomfort induced by carrying a backpack.

It was hypothesized that:

1. The patterns of $T_{sk}$ would be similar between SEXES at all stages of the protocol.
2. FEMALES would be more prone to cold discomfort due to intense blood flow redistribution and less to warm discomfort due to lower sweating compared to MALES.
3. Cold discomfort would occur during resting phases and warm discomfort due to sweating during exercise with different underlying mechanisms (local or overall).
4. The condition with BACKPACK would have a strong influence on regional $T_{sk}$ and regional thermal votes in the back region compared to the NO BACKPACK condition.
6.2. Methods

All participants completed a pre-test session and one experimental session each separated by at least 48 hours. Males performed an additional experimental session with the two conditions in a balanced order: BACKPACK and NO BACKPACK. The experimental sessions were performed at the same time of day to prevent circadian effects, though different participants were tested at different times and therefore inter-individual variations in circadian thermal status was not controlled.

6.2.1. Participants

Eight males and eight females, all physically active, were recruited among the student population of Loughborough University with various exercise backgrounds (football, hockey, running). They all signed an informed consent after explanation of the study methods and goals.

6.2.2. Pre-Test session

The pre-test session involved anthropometric measurements of height and body mass. Skinfold thickness measurements using a Harpenden caliper were performed at 7 sites across the right side of the body for the calculation of body density (Jackson and Pollock, 1978) and then converted into % body fat using Siri’s equation (1956).

The second part of the pre-test session consisted of a sub-maximal $\dot{V}O_2\text{max}$ test on the treadmill (h/p cosmos mercury 4.0, Nussdorf-Traunstein, Germany). The test was designed following the guidelines of ACSM (2004) using a ramp test with 5*4min increments in speed (0.5 km.h$^{-1}$) starting at 2 km.h$^{-1}$ on the treadmill with 15% gradient. Maximal aerobic power ($\dot{V}O_2\text{max}$) was calculated based on Epstein et al. (1999). A relative workload of 55% $\dot{V}O_2\text{max}$ was chosen to mimic real life conditions of a normal day-hike (uphill walking). The walking speed was adjusted for males without a backpack to match the workload with backpack. Participants were familiarised with the subjective evaluation scales (thermal sensation, thermal comfort, RPE) during the first stages of the submaximal test. Scales corresponded to the ones used for the generic skin temperature mapping protocol (cf 2.4.7). Overall wetness sensation ($WS_{overall}$) was rated for on a 7-point scale (dry to dripping wet) and self reported by the participants for local body regions ($WS_{local}$).
6.2.3. Protocol

The experimental protocol (Figure 6.1) was following a chronology encountered by recreational hikers during a single-day event. All specific phases of a day-hike were represented but shortened due to laboratory availability and recruitment constraints. For all participants, the backpack mass was adjusted upon arrival to the laboratory to 10% of the measured body mass. This relative mass was chosen to represent the normal carriage for a single day-hike. The backpack was the same for all participants (Quechua Forclaz 50L) and filled with clothing, a bottle of 1.5L water, and packed lunch boxes. Additional mass was then added when appropriate by inserting custom-made metal disks (0.1kg, 0.5kg, 1kg) in the boxes in the upper part of the backpack.

Participants were advised on fluid intake for maintenance of euhydration and to avoid alcoholic consumption and strenuous exercise within 24 hours prior to testing. The protocol started with a 5°C, 50% rh cold exposure at rest and then 5 minutes of walking at 5 km.h⁻¹ speed and 0% gradient for all participants. Air temperature (Tₐ) was modified from 5°C, 50% rh to 15°C, 60% rh during the first stage (ascent phase) in order to promote sweating in the second half of the ascent. This kind of variability in weather conditions has been reported in a field study by Ainslie et al. (2002) during a 12km mountainous walk. Pilot tests clearly showed that 30 minutes was sufficient to increase Tₐ by 10°C in the climatic chamber in a reproducible manner. Air velocity (2.8 m.s⁻¹) was turned on at 65 minutes for a duration of 5 minutes (chill phase) with the participant sitting at rest (without the backpack, no back rest) and

![Figure 6.1](image-url)
facing the fans (JS Humidifiers, Littlehampton, UK) at a distance of 2.1 meters (Figure 6.2, picture 3).

Figure 6.2 Pictures of the 4 main stages of the experimental protocol in the climatic chamber, showing evolution in clothing ensemble and type of activity (PRE, ASCENT1, ASCENT2, CHILL, DESCENT).

Five different sets of infrared measurements were taken with the subject standing in an anatomical position: 5 minutes after entering the climatic chamber before hiking (PRE), after 30 minutes of uphill walking (ASCENT 1), after 60 minutes of uphill walking (ASCENT 2), after exposure to air velocity (CHILL), and after 30 minutes of downhill walking (DESCENT). Infrared measurements were preceded by subjective assessment (thermal sensation, thermal comfort, wetness sensation, RPE) whilst walking or sitting.

Participants wore a standardised clothing ensemble adjusted to their body size: swimming trunks (Tribord), sports bra for females (Sportance 300, Kalenji), a pair of trousers (Forclaz 900 Lady, Forclaz 900 Men, Quechua), a T-shirt with no under-arm mesh yoke (Deefuz, Quechua), a fleece top (Forclaz 50, Quechua), hiking socks (Forclaz 100, Quechua), and a pair of hiking boots (Forclaz 100 Novadry Lady, Forclaz 500 Men, Quechua). The overall ensemble corresponded to a total clothing insulation of 1.3 Clo based on thermal manikin measurements (Newton, MTNW, Seattle, USA).

Infrared measurements were taken immediately at the end of each stage in close proximity to the treadmill. Participants were assisted by one of the experimenters in the short stripping phase (backpack, fleece top, T-shirt, trousers) to allow quick and dry exposure (towel) of the bare skin in 15 seconds. Pilot tests with contact sensors highlighted that the course of $T_{sk}$ variations was modified by less than 0.5°C during the stripping and measurement phase (less than 90 seconds in total) in various body regions. The author is confident that the $T_{sk}$ patterns closely reflect the patterns that were present underneath the clothing, and this is in line with findings from others.
(Livingstone et al., 1988). Limitations regarding the exact value for absolute $T_{sk}$ cannot be ruled out. However the procedure was standardised and errors should have been consistent throughout the protocols.

Pulse rate, an indicator of heart rate (HR), was monitored using a pulse oximeter (MedView, UK) at the tip of the index in a stable position every 10 minutes during the protocol. This measurement was preferred to classical HR belt measurement as this would have modified regional $T_{sk}$, regional sweat rate and the subsequent thermal or wetness perceptions. Measurements proved to be valid at the walking speeds encountered in the protocol as there were minimal motion artefacts.

Oxygen uptake was measured using the Douglas bag method 20 minutes (15 minutes of uphill walking) and 90 minutes into the protocol (15 minutes of downhill walking).

Core temperature was monitored throughout the whole protocol using a rectal thermistor (Grant Instruments, Cambridge, UK) and recorded every 1 minute using a data logger (1000 series Squirrel Eltek/Grant, Grant Instruments, Cambridge, UK).

Body mass and clothing mass were recorded upon arrival at the laboratory and immediately after the session using an electronic scale (Mettler Toledo, 150kg, Mettler Toledo, Leicester, UK). Body sweat loss was calculated from weight loss, adjusted for water intake and corrected by respiratory and metabolic mass losses.

### 6.2.4. Analysis

All infrared thermograms were processed using the custom-made MATLAB procedure in order to obtain group-averaged body maps at each phase of the protocol as well as quantitative $T_{sk}$ data for predefined regions (see Chapter 2). Three groups could be distinguished from the recruitment and the different protocol conditions; they were labelled as follow: FEMALES, MALES (in both cases wearing a backpack) and MALES_NB (same group of males with no backpack). Relative $T_{sk}$ body maps were also produced at each protocol stage and they reflected the body map relative to the group mean skin temperature ($T_{sk}$) at each stage.

Mean skin temperature ($T_{sk}$) was calculated as the average of all the pixels measured on the entire body surface by the 5 different thermograms, except for the covered body parts (groin and feet). Statistical Analysis was conducted using SPSS 16.0. Two separate 2-way repeated measures ANOVA were used to investigate the main effect.
of TIME and SEX (between-subject) on one hand and TIME and BACKPACK (within subject) on the other hand.

Dependent variables were $T_{re}$, $T_{sk}$, and $T_{sk,local}$. Holm-Bonferroni corrections were applied to allow for multiple comparisons when comparing the different body regions investigated. A Pearson-correlation coefficient was obtained following regression analysis between $T_{sk}$ parameters (local and overall) and body fat parameters or perceptual parameters (local and overall).
6.3. Results

6.3.1. Participants

The participants’ characteristics, aerobic fitness level, walking speed and predicted metabolic rate during both trials are presented in Table 6.2.

6.3.2. Skinfold thickness

Skinfold thickness at 7 locations is presented in Table 2.

Table 6.1. Participants’ skinfold thickness at 7 sites and sum of skinfolds for each individual participants (f = females; m = males).

<table>
<thead>
<tr>
<th>Participant</th>
<th>chest (mm)</th>
<th>triceps (mm)</th>
<th>midaxillary (mm)</th>
<th>subscapular (mm)</th>
<th>suprailiac (mm)</th>
<th>abdominal (mm)</th>
<th>thigh (mm)</th>
<th>Sum of skinfolds (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>f1</td>
<td>24.0</td>
<td>22.2</td>
<td>16.0</td>
<td>38.0</td>
<td>35.0</td>
<td>23.2</td>
<td>32.0</td>
<td>190.4</td>
</tr>
<tr>
<td>f2</td>
<td>9.0</td>
<td>18.2</td>
<td>9.8</td>
<td>10.3</td>
<td>21.0</td>
<td>22.0</td>
<td>26.0</td>
<td>116.3</td>
</tr>
<tr>
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<td>22.3</td>
<td>10.9</td>
<td>26.4</td>
<td>28.3</td>
<td>20.6</td>
<td>33.0</td>
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</tr>
<tr>
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<td>20.8</td>
<td>21.0</td>
<td>13.2</td>
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<td>8.2</td>
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<td>14.9</td>
<td>26.3</td>
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</tr>
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<td>f6</td>
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* significantly different from females at p<0.05
** significantly different from females at p<0.01

From the skinfold thickness measurement, 5 out of 7 body regions were found significantly different between males and females. The sum of skinfolds was 63% larger for females compared to males. From the group of females, four of them were in the luteal phase of the menstrual cycle (f2, f4, f7, f8) and four of them were in the follicular phase (f1, f3, f5, f6).
Table 6.2. Participants’ anthropometric characteristics (mean ± SD and range) and predicted aerobic fitness level for three distinct categories of body fat content (f = females, m = males)

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<th>Participant no</th>
<th>Body fat content (%)</th>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Body Mass (kg)</th>
<th>A_Du/M (cm².kg⁻¹)</th>
<th>Predicted $\overline{VO}_{2,max}$ (mL.min⁻¹.kg⁻¹)</th>
<th>Uphill walking (%) with backpack</th>
<th>Downhill walking (%) with backpack</th>
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<td>(40-71)</td>
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<td>(43-59)</td>
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$A_{Du}$ = body surface area; $Mass$ = body mass; $A_{Du}/M$ = body surface to mass ratio; $\overline{VO}_{2,max}$ = predicted relative maximal oxygen uptake as calculated from Epstein et al. (1999).

*significantly different from females at p<0.05 and ** p<0.01

Max $\overline{VO}_{2,max}$
6.3.3. Evolution of thermoregulatory and overall perceptual responses

6.3.3.1. Rectal temperature, mean skin temperature, body sweat loss

This section introduces the main thermoregulatory responses induced by the simulated hike for FEMALES, MALES with backpack and males with no backpack (MALES_NB).

The effect of SEX was significant for rectal temperature ($T_{re}$) over the whole protocol ($p<0.05$), $T_{re}$ being higher for females than males and this was most pronounced during the ASCENT and CHILL exposure phases (Figure 6.3). There was also a significant TIME*SEX interaction effect, highlighting the larger decrease in $T_{re}$ for females after the CHILL exposure phase (-0.9± 0.2°C) compared to males (-0.7 ± 0.1°C). When data were analysed relatively to pre-exercise values, there was no overall SEX effect but still the significant interaction effect.

The effect of BACKPACK was not significant on $T_{re}$ over the whole protocol with no interaction effect. This indirectly confirmed that the metabolism was properly adjusted between the two conditions (load and no load).

There was a tendency for a lower $T_{sk}$ for females throughout the protocol ($p=0.053$). Significant differences were observed at three specific stages (ASCENT 1, ASCENT 2 and CHILL). The interaction TIME*SEX was significant ($p<0.05$) with a significantly larger increase for females between CHILL and DESCENT compared to males ($+1.5±0.3°C$ females vs $+0.8±0.3°C$ males, $p<0.05$).

There was no significant overall effect of BACKPACK on $T_{sk}$ despite specific differences being highlighted during the ascent (ASCENT 1 and ASCENT 2). The interaction effect was significant with the opposite $T_{sk}$ variations from PRE to ASCENT 1: increase for males with backpack and decrease for males without backpack. From PRE to ASCENT 2, $T_{sk}$ remained relatively constant for males with backpack ($+0.3 ± 0.7°C$) and significantly decreased for males without backpack ($-0.5 ± 0.7°C$).

Body sweat loss was similar between females and males ($176 ± 36 g.m^{-2}.h^{-1}$ vs $210 ± 62 g.m^{-2}.h^{-1}$, $p=0.21$). It was also similar with and without backpack ($210 ± 62 g.m^{-2}.h^{-1}$ vs $211 ± 56 g.m^{-2}.h^{-1}$, $p=0.97$) confirming the similarity in the overall strain.
Figure 6.3. Evolution of rectal temperature (°C) and mean skin temperature (°C) for the group of 8 females and 8 males in a condition with load carriage and no load (NB) during a simulated hike. **Terrain** = Ascent: uphill walking with 15% gradient at 55% VO\(_{2\text{max}}\) in a 15°C environment. **CHILL**: 5-min exposure to 10km.h\(^{-1}\) air velocity. **Descent**: downhill walking with 15% gradient at 20% VO\(_{2\text{max}}\) in a 15°C environment. **Clothing ensemble** = L1: Layer 1 (Tshirt) L2: Layer 2 (Fleece) BP: Backpack (10% body mass) with trousers, underwear, socks and hiking boots.

*significantly different from females (p<0.05) ¤ significantly different from NB condition (p<0.05).
On top of the above thermoregulatory parameters, it was clear that the simulated hike
induced a larger cardiovascular strain in the first part of the protocol (uphill walking)
with significantly larger HR for females compared to males (141 ± 18bpm vs 121 ±
13bpm at 60 minutes, p<0.05). There were no sex differences in HR during the
CHILL exposure and DESCENT. Moreover no HR differences were reported for
males between the conditions with and without load over the whole protocol.
HR was significantly lower during the downhill stage (females: 88 ± 12bpm, males:
88 ± 12bpm, males_NB: 88 ± 10bpm) compared to the uphill stage.
Lastly, RPE was similar between females and males (with and without backpack) for
both the uphill stage (♀:12.0 ± 0.8 vs ♂:11.4 ± 1.2 vs ♂_NB: 11.3 ± 1.3, NS) and the
downhill stage (♀:10.9 ± 1.1 vs ♂:10.3 ± 1.5 vs ♂_NB: 10.3 ± 1.2, NS). Overall, the
uphill stage was perceived significantly more strenuous than the downhill stage
(p<0.01) but only to an average of 1 unit on the RPE scale.

6.3.3.2. Thermoregulation and overall body fat content
A significant negative relationship was found between \( T_{sk} \) and %BF (combining
values from females and males with backpack) for the all stages except DESCENT (\( r =
-0.63 \) at PRE p<0.01; \( r = -0.55 \) at ASCENT 1 p<0.05; \( r = -0.63 \) at ASCENT 2
p<0.01; \( r = -0.71 \) at CHILL p<0.01). The same correlation coefficients were obtained
for the relationships between \( T_{sk} \) and sum of 7 skinfolds.
Furthermore, a positive relationship was found between \( T_{re} \) and %BF, also for the
PRE and ASCENT stages (\( r = -0.66 \) at PRE p<0.01; \( r = -0.77 \) at ASCENT 1 p<0.01;
\( r = -0.64 \) at ASCENT 2 p<0.01).
The relationships are presented for \( T_{sk} \) and \( T_{re} \), specifically at PRE and ASCENT 2
(Figure 6.4). From the analysis of the groups separately, the only significant
correlation between \( T_{sk} \) and %BF was found for females at PRE (\( r = -0.79 \) p<0.05).
For the relationship between \( T_{re} \) and %BF, a positive correlation was obtained for
females at PRE (\( r = 0.75, p<0.05 \)) and males at ASCENT 1 and ASCENT 2 (\( r = 0.70 \)
and \( r = 0.74, p<0.05 \)), CHILL (\( r = 0.81, p<0.01 \)) DESCENT (\( r = 0.72, p<0.05 \)).
Figure 6.4: Mean skin temperature ($\bar{T}_{sk}$) and rectal temperature ($T_{re}$) in relation to body fat percentage (body fat %) before hiking at PRE (A - C) and ASCENT 2 after 60 minutes uphill walking with a backpack at 55% $\dot{V}O_{2,max}$ (B - D) in a 15°C environment for females (▲), males (●) and all participants wearing a backpack combined (■).

### 6.3.3.3. Mean skin temperature and overall subjective votes

Neither overall thermal sensation ($TS_{\text{overall}}$) nor overall thermal comfort ($TC_{\text{overall}}$) were correlated with $\bar{T}_{sk}$ at any stage of the protocol and any group (FEMALES, MALES, MALES_NB). A significant correlation was found at the CHILL stage between $TS_{\text{overall}}$ and $\bar{T}_{sk}$ when the 3 groups were combined ($r = 0.55$, $p<0.05$). Combining data from females and males (with backpack), there was a significant relationship between $TS_{\text{overall}}$ and $\bar{T}_{sk}$ at ASCENT 1 ($r = 0.51$, $p<0.05$) and at CHILL ($r = 0.63$, $p<0.01$).

Lastly, when data from different stages were plotted together, a significant correlation was highlighted for the combination CHILL+DESCENT between $TS_{\text{overall}}$
and $\bar{T}_{sk}$ on one hand ($r = 0.69, p<0.01$) and TCoverall and $\bar{T}_{sk}$ on the other hand ($r = 0.53, p<0.05$). This was the case for all groups combined ($n=24$) as well as for 2 groups combined ($n=16$; females+males; males+males without load) and each group of males and females (Figure 6.5).

![Figure 6.5: Overall thermal sensation in relation to mean skin temperature ($\bar{T}_{sk}$) for two specific stages combined (CHILL = seated in a 15°C environment with a 10 km.h$^{-1}$ wind exposure, DESCENT = after 30 minutes of downhill walking at 20% $V_{\text{O}_{2}\text{max}}$ in a 15°C environment). Data and relationships are presented for the group of females (▲), males (■) males_nb (+) as well as the relationship for all participants combined (•).](image)

### 6.3.3.4. Overall subjective votes

The evolution of overall thermal votes over the whole protocol is presented in Figure 6.6. It indicates that the worst TCoverall was perceived for males (with and without load) after walking uphill at 55% $V_{\text{O}_{2}\text{max}}$ (ASCENT 1 and 2) associated with warm and wet sensations, whereas it occurred after wind exposure for females (CHILL) associated with cool and moist sensations. Overall discomfort was significantly larger for females compared to males (1.5 scale unit) only at this specific CHILL stage ($p<0.05$).

$T_{\text{Soverall}}$ was significantly higher for males compared to females (2.5 scale units) before hiking which correspond to 10 minutes at 5°C in a resting condition. No other SEX differences were observed for the rest of the protocol. The effect of
**BACKPACK** was highlighted only after 30 minutes of walking uphill with a higher $T_{S_{\text{overall}}}$ for the load compared to the no load condition (1.5 scale units). $W_{S_{\text{overall}}}$ differed in the first stage of the protocol with males reaching a significantly higher degree of wetness at ASCENT 1 (1 scale unit) compared to females and males without load. After 60 minutes of walking (ASCENT 2), all participants reached wetness in the range between 3 and 5 on the wetness scale ($\text{wet}$). Males with backpack were significantly less wet than males with backpack at the end of the DESCENT.

*Figure 6.6*: Overall perceptual responses (thermal sensation, wetness sensation, thermal comfort) for the 3 groups: females (▲), males (■) males without load (+) at all stages of the hiking protocol (PRE, ASCENT 1, ASCENT 2, CHILL, DESCENT). * significantly different from females (p<0.05) ‡ significantly different from males_nb (p<0.05).
To summarise, it is important to note the delayed increase in WS\textsubscript{overall} for females and males without backpack (observed at ASCENT 1), no differences in TS\textsubscript{overall}, WS\textsubscript{overall} and TC\textsubscript{overall} for all groups at ASCENT 2, the larger discomfort for females at CHILL, as well as the return to a more comfortable state at DESCENT with \textit{slightly warm} and only \textit{dry} to \textit{moist} sensations for all participants.

6.3.4. Patterns of skin temperature distribution

The following figures (Figure 6.7, 6.8, 6.9, 6.10, 6.11) provide quantitative data about the T\textsubscript{sk} topography for the 3 groups. The absolute T\textsubscript{sk} maps correspond to the arithmetic average of morphed thermograms of the 8 individuals in each group (pixel by pixel) at each specific stage. The relative maps are obtained by dividing the matrix of the group absolute map by the group T\textsubscript{sk} at that specific stage. This allows for a valid comparison between sex and between the load and no load conditions in terms of similarities or differences in the T\textsubscript{sk} patterns. Furthermore, the differences between sex and between load conditions in absolute and relative T\textsubscript{sk} (relative to each group T\textsubscript{sk}) are presented in Table 6.3.
Figure 6.7: Group-averaged maps of absolute (left panel) and relative (right panel) skin temperature at rest after 5 minutes standing in a 5°C environment (PRE) with a standard clothing ensemble (T-shirt, fleece, trousers) for females, males and males with no backpack (NB) after morphing individual images of the 8 participants of each group into a reference body shape.
Figure 6.8: Group-averaged maps of absolute (left panel) and relative (right panel) skin temperature at rest after 30 minutes of uphill walking (15% gradient) at 55% $V_{O_2 \text{max}}$ in a 15°C environment (ASCENT 1) with a standard clothing ensemble (T-shirt, fleece, trousers) for females, males and males with no backpack (NB) after morphing individual images of the 8 participants of each group into a reference body shape. Relative = relative to each condition mean skin temperature ($=1$).
Figure 6.9: Group-averaged maps of absolute (left panel) and relative (right panel) skin temperature at rest after 60 minutes of uphill walking (15% gradient) at 55% $V_{O_{2\text{max}}}$ in a 15°C environment (ASCENT 2) with a standard clothing ensemble (T-shirt, trousers) for ♀ females, ♂ males and males with no backpack (♂ NB) after morphing individual images of the 8 participants of each group into a reference body shape. Relative = relative to each condition mean skin temperature (=1).
Figure 6.10: Group-averaged maps of absolute (left panel) and relative (right panel) skin temperature at rest after 5 minutes of 2.8 m.s$^{-1}$ wind exposure at 2 meters distance (CHILL) with a standard clothing ensemble (T-shirt, trousers) for ♀ females, ♂ males and males with no backpack (⪼NB) after morphing individual images of the 8 participants of each group into a reference body shape. Relative = relative to each condition mean skin temperature (=1).
Figure 6.11: Group-averaged maps of absolute (left panel) and relative (right panel) skin temperature at rest after 30 minutes of downhill walking (15% gradient) at 20% $\dot{V}O_2$ in a 15°C environment (DESCENT) with a standard clothing ensemble (T-shirt, trousers) for ♀: females, ♂: males and males with no backpack (♂NB) after morphing individual images of the 8 participants of each group into a reference body shape. Relative = relative to each condition mean skin temperature (=1).
Table 6.3: Significance levels of comparisons for ABSOLUTE skin temperature between sex (FEMALES vs MALES) and between the load and no load conditions for males (MALES vs MALES_NB) at all stages of the protocol (PRE, ASCENT 1, ASCENT 2, CHILL, DESCENT) for both uncorrected differences and Holm-Bonferroni corrected (at p<0.05).

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Table 6.4: Significance levels of comparisons for RELATIVE skin temperature between sex (FEMALES vs MALES) and between the load and no load conditions for males (MALES vs MALES_NB) at all stages of the protocol (PRE, ASCENT 1, ASCENT 2, CHILL, DESCENT) for both uncorrected differences and Holm-Bonferroni corrected (at p<0.05).

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<tr>
<td>DESCENT</td>
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Lateral body regions:
- 30 Low Abdomen
- 31 Upper Abdomen
- 32 Chest
- 33 Armpit
- 34 Scapular
- 35 Cheek

Significantly different from males with backpack at p<0.05 (values indicate the difference males – females and males – males_nb).
6.3.5. Local skin temperature and local subjective votes

The 2-way repeated measures ANOVA revealed a significant overall effect of SEX on $T_{sk,local}$ when all stages and regions were taken into account with an overall average regional difference of 0.8°C (lower for females). As highlighted by Table 6.3, significant differences in $T_{sk,local}$ were however limited to a small number of regions (maximum: 11 out of 35 at ASCENT 2). The regions with consistent differences throughout the protocol were located in the lower limbs (thigh, hamstrings, popliteal fossa, calves) with lower $T_{sk}$ of approximately 2°C for females compared to males. The hip region as well as the anterior arms were also colder for females compared to males at ASCENT 2.

The effect of BACKPACK was also limited to a small number of regions (maximum 11 out of 35 at ASCENT 2) with no overall effect. The differences were notably observed throughout the uphill stages (ASCENT 1 and ASCENT 2) especially in the clavicular, chest, upper and lower back regions. A specific analysis was performed in order to emphasize the discrete regional influence of the pads in contact with the skin based on the absolute body maps (Figure 6.12).

![Figure 6.12: Average temperature difference (°C) between backpack and no backpack conditions based on four discrete regions defined by the backpack construction (pads in contact with the skin) on the final average body maps of absolute $T_{sk}$ at all stages of the protocol (PRE, ASCENT 1, ASCENT 2, CHILL, DESCENT).](image-url)
This observational data highlight the relative importance of the lower back pad on increasing the $T_{sk}$ of exercising hikers with additional load, inducing an average of 2.7°C warmer $T_{sk}$ measured in the lower back at ASCENT and DESCENT compared to the no load condition.

The overall effect of SEX was not significant neither on $T_{Slocal}$, $W_{Slocal}$ nor $T_{Clocal}$ despite $T_{sk}$ differences as large as 2.9°C locally.

For specific stages, there was a significant difference in $W_{Slocal}$ only for the armpits at ASCENT 1 (females +1 vs males +3, p<0.05) and for the face at ASCENT 2 (females 0 vs males +4, p<0.05).

The overall effect of BACKPACK was not significant neither on $T_{Slocal}$, $W_{Slocal}$ nor $T_{Clocal}$.

Only few regions displayed significant differences at specific stages. Lower back was perceived warmer for backpack compared to no backpack condition (ASCENT 1: +5 vs +2, p<0.01; ASCENT 2: +5 vs +4, p<0.05; DESCENT: +4 vs +1.5, p<0.01) similar to the abdomen (DESCENT +3 vs +1.5, p<0.05).

In terms of $W_{Slocal}$, the participants with backpack perceived their lower back wetter over the most of the protocol (males vs males_NB; ASCENT 1: +3 vs 0, p=0.1, ASCENT 2 +4 vs +1, p<0.05, DESCENT: +2 vs +0.5, p<0.05) as well as their armpits at DESCENT (males +3 vs males_NB +2, p<0.05).

$T_{Clocal}$ was significantly better for males without a backpack at ASCENT 1 for abdomen (males -2.5 vs males_NB -1, p<0.05) and upper back (males -2.5 vs males_NB -1.5, p<0.05), at ASCENT 2 for the lower back (males -2.5 vs males_NB -1, p<0.05), at DESCENT for the upper back and lower back (males -2.5 vs males_NB -0.5, p<0.01).

The contribution of different body regions to overall discomfort was difficult to assess especially in such a scenario where the dynamics of regional votes were very similar. At PRE, back of the hands and face were mainly responsible for cold discomfort especially in females. At ASCENT 2, the lower back, face and armpits are the worst comfort votes (warm and wet). At CHILL, cold discomfort was mainly due to the face, especially in females and at DESCENT, there was only moderate discomfort associated with local discomfort in the armpits and lower back.

Over the five stages, there was a very limited number of significant correlations between thermal votes ($T_{Slocal}$, $T_{Clocal}$, $T_{Soverall}$, $T_{Coverall}$) and $T_{sk,local}$ as presented in table 6.5. Only 38 out 660 correlations (20 for females, 15 for males, 3 for
males_NB) were significant with no regions showing consistent results over the different protocol stages.

Table 6.5 Correlation coefficients table (r values) for the relationship between thermal votes at different body regions and overall/local skin temperatures for the three groups: females, males, and males without backpack (NB) at the five protocol stages.

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TS local: Local thermal sensation, TC local: local thermal comfort, TS overall: overall thermal sensation, TC overall: overall thermal comfort. **Bold** values correspond to the best r values for overall votes. "#" correspond to significant correlations at p<0.05 (no Bonferroni correction applied)

The data were then combined for all three groups (ALL) and the groups of females and males wearing a backpack (B) in Table 6.6 (upper table). Significant correlations were mainly observed at ASCENT 1 and CHILL without regional consistencies.
Table 6.6 Correlation coefficients (r values) for the relationship between thermal votes at different body regions and overall/local skin temperatures for all groups combined (ALL: n=24) and the two groups wearing a backpack (B: n=16) at the five protocol stages (upper table).

Data from uphill stages and chill+downhill stages are combined for all groups (ALL: n=24), the two groups wearing a backpack (ALL MALES) and the three separate groups (lower table).

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<th>L.BACK</th>
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</table>

TS local: Local thermal sensation, TC local: local thermal comfort, TS overall: overall thermal sensation, TC overall: overall thermal comfort. NB: no backpack

Bold values correspond to the best r values for overall votes.

Correspond to significant correlations at p<0.05 (no Bonferroni applied)
The combination of several stages (Table 6.6 lower table) highlighted three main specificities. Firstly, a correlation between $TS_{\text{overall}}$ and $T_{\text{sk}}$ at the limbs and extremities (arms, legs, hands, face) was found for the uphill stages with a negative relationship for the arms and positive for the legs, hands and face. Secondly, there were good correlations between overall thermal votes ($TS_{\text{overall}}$ and $TC_{\text{overall}}$) and $T_{\text{sk}}$ in the upper body (chest, abdomen, upper and lower back) for CHILL and DESCENT. Lastly, face $T_{\text{sk}}$ seemed to be a good predictor (significant positive correlations) of $TS_{\text{local}}$ and $TS_{\text{overall}}$ during both parts of the protocol (uphill and downhill).

Using a between-regions approach (within-subject), the distribution of local thermal votes ($TS_{\text{local}}$ and $TC_{\text{local}}$) was analysed in relation to the distribution of $T_{\text{sk,local}}$ for the 11 corresponding large regions investigated. Significant correlations were found between distribution of $TS_{\text{local}}$ across the body and distribution of $T_{\text{sk,local}}$ at ASCENT 1, ASCENT 2 and DESCENT ($r = 0.91$, $p<0.01$; $r = 0.81$, $p<0.05$; $r = 0.59$, $p<0.05$). However, this was not confirmed when distributions for each individual were analysed separately with a large variety of correlations ($r$ varying from -0.7 to 0.8). In this context, the distribution of group averages (for $T_{\text{sk,local}}$ and $TS_{\text{local}}$) was providing information not representative of individual distributions.

Using a between-subjects approach, $TS_{\text{local}}$ that correlated the most throughout the protocol with $TS_{\text{overall}}$ was obtained at the face for all groups combined or groups separately (from $r = 0.86$ to $r = 0.89$, $p<0.01$). $TC_{\text{local}}$ that correlated the most throughout the protocol with $TC_{\text{overall}}$ was obtained at the chest for all groups combined or groups separately (from $r = 0.60$ to $r = 0.69$, $p<0.05$).

6.3.6. Local skin temperature and local skinfold thickness

The measurements of 7 skinfold thickness sites were analysed in association with $T_{\text{sk,local}}$ of the same regions from the whole-body $T_{\text{sk}}$ segmentation.
Table 6.7 Correlation coefficients table (r values) for the relationship between local skin temperatures (°C) and local skinfold thickness (mm) at 7 different body regions for the three groups (females, males, males_nb; n=8 for each) and the groups with backpack (B: n=16).

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Grey: significant correlations at p<0.05 and grey at p<0.01 (no Bonferroni correction applied)

The thigh region displayed a consistent and significant negative relationship between skinfold thickness and T_{sk,local} at all stages. This significant correlation was found for the group of females only at PRE and it is important to note the large difference between the two groups in thigh skinfold (cf. Table 6.1) which induces a bias in the interpretation.

6.4. Discussion

The aim of the present study was to provide a descriptive approach of the combined role of external (CLOTHING, AIR TEMPERATURE, AIR VELOCITY) and internal determinants (EXERCISE ACTIVITY) of T_{sk}. The influence of these determinants during a real-life scenario was observed on both thermoregulatory and perceptual responses. The applied integrated protocol design prevented from an analysis to be performed on one specific determinant listed above; however it was possible to specifically investigate the overall influence of SEX, and thanks to two identical conditions for males, the influence of wearing a BACKPACK (additional insulation). Chapter 3 was also looking at SEX differences during an exercising protocol, yet in a semi-nude and more controlled condition (similar physical fitness between sexes). The discussion will therefore bring some indirect insights in the discrepancy between clothed and unclothed conditions.

The main findings were that SEX differences on thermal subjective responses were minimal throughout the protocol despite significant differences on thermoregulatory
parameters (lower $\text{T}_{sk}$, higher $T_{re}$ in females). Some regional specificities between males and females were highlighted through the body mapping approach with lower absolute $T_{sk}$ for females compared to males in some locations (lower limbs) but not all. Thermal perceptions differed between sexes only during the resting phases. Wearing a BACKPACK as opposed to no backpack (at the same relative workload) had only a very limited influence on both thermoregulatory and perceptual responses. The major difference was observed during the first stage of the ascent (from PRE to ASCENT 1) where $\overline{T}_{sk}$, $T_{sk,local}$, $T_{overall}$, $WS_{overall}$, $T_{local}$ were lower for males without a backpack compared to the condition with a backpack. Overall, $T_{sk,local}$ differences were most pronounced in the lower back (+3°C with backpack) during the exercising phases. In this study with clothed participants, no consistent correlations between $T_{sk}$ and thermal votes were found, neither when groups were combined nor when protocol stages were combined.

6.4.1. The influence of sex during a simulated hill walk

6.4.1.1. Overall thermoregulatory responses

Sex differences were found on rectal temperature ($T_{re}$) with females exhibiting 0.3°C higher values compared to males with an exact parallel evolution throughout the first stages of the protocol (from PRE to ASCENT 2, see Figure 6.3). The initial higher $T_{re}$ for females was in agreement with Cunningham et al. (1978) with the important indication that half of the female group was in the luteal phase which is known to elevate resting core temperature by approximately 0.5°C (Stephenson and Kolka, 1985). During exercise, heat production from females was smaller (same relative workload but lower physical fitness and lower body mass) but the initial $T_{re}$ difference remained constant, most likely due to the larger tissue insulation (subcutaneous fat and lowered $T_{sk}$) for females compared to males. $T_{re}$ remained relatively steady from ASCENT 1 to ASCENT 2 for both groups which suggest thermal equilibrium was almost reached. This was in part related to the reduced clothing insulation (fleece layer removed at the end of ASCENT1: long sleeves to short sleeves) with more skin surface areas exposed allowing larger heat loss from the upper limbs. The regional influence of this clothing adjustment will be discussed in 4.1.2. There was tendency for a larger impact of this adjustment on $\overline{T}_{sk}$.
for females than males (ASCENT 1 to ASCENT 2: ♀ -0.5 ± 0.2°C vs ♂ -0.3 ± 0.4°C, p=0.012).

Over the different stages, $\bar{T}_{sk}$ remained between 28°C and 29.5°C for both groups. This is slightly lower than the earlier reported range of 29-31°C preferred by hill walkers during outdoor activities where participants could freely adjust clothing (Pugh, 1969). Our values were below the comfortable range and participants indeed experienced cold as well as moderate warm discomfort throughout the protocol. At the end of the descent, $\bar{T}_{sk}$ reached 29.5°C for males and females and this corresponded to the highest levels of comfort, associated with low wetness sensation and slightly warm sensation.

In our experiment, positive and negative work (uphill and downhill phases) was performed at the same speed and therefore not matched for total heat production. The very low intensity during the downhill stage reflected a real life scenario and was associated to a much lower heat production for our negative work exercise. The distribution of body temperatures yet appeared to be slightly different during positive and negative works which is in agreement with the findings from Nadel et al. (1972). In controlled thermoneutral condition, they found a 1.2°C higher quadriceps muscle temperature, a 3°C higher $\bar{T}_{sk}$ and 0.7°C lower $T_{core}$ during negative work as opposed to positive work of the same total heat production. Our results, though based on two different heat productions, showed a significantly higher $\bar{T}_{sk}$ at DESCENT compared to ASCENT 1 (same clothing ensemble) in both groups (+0.7°C on average).

Females were more affected than males by changes in external factors such as wind exposure and the lower exercise intensity for downhill walking. In females, the drop in $T_{re}$ was more pronounced from ASCENT 2 to DESCENT compared to males. This greater sensitivity to external factors (leading to a larger drop in $T_{re}$) was not correlated with metabolic heat production (yet lower for females) but this was associated with anthropometrical characteristics such as height and weight ($r = -0.74$, p<0.01), and consequently surface area ($r = -0.76$, p<0.01) and surface area-to-mass ratio ($r = 0.59$, p<0.05). The drop in $T_{re}$ during the downhill stage was larger for small and light participants with a large surface area-to-mass ratio. Moreover, the drop in $T_{re}$ was associated with a larger increase in $\bar{T}_{sk}$ for females (from CHILL to DESCENT). This mechanism may have contributed to a certain extent to the
continued drop in $T_{re}$ for females, circulatory flow being redistributed to the periphery (lower metabolic demand in the muscles), warming up the shell and therefore favouring heat dissipation. Body sweat loss over the protocol was similar between sexes but intermediate values (at ASCENT 2 or CHILL) were however not recorded.

At DESCENT, $T_{re}$ decreased to pre-exercise values for females. This situation was clearly similar to thermoregulatory responses observed by Weller et al. (1997) using 120min of uphill walking ($5 \text{ km.h}^{-1}, 10\% \text{ incline} : 60\% \dot{V}O_{2,\text{max}}$) followed by level walking ($5 \text{ km.h}^{-1}, 0\% : 30\% \dot{V}O_{2,\text{max}}$).

Unlike Chapter 3 (unclothed male and female runners) where $\overline{T}_{sk}$ was correlated with metabolic heat production, this relationship was not observed in the present study. In contrast $\overline{T}_{sk}$ was negatively correlated with %BF when the groups of females and males were combined (n=16) at all stages except DESCENT (same $\overline{T}_{sk}$ for both groups). This echoes well the results from Chapter 3 where the pooled data highlighted this specific relationship but caution was required for interpretation considering the clearly separated $\overline{T}_{sk}$ values between groups. In the present study, negative relationships between $\overline{T}_{sk}$ and %BF were highlighted within all groups and this was even significant for the group of females at PRE (Figure 6.4). The population of clothed hikers was slightly more spread in body fat content compared to the semi-nude runners from Chapter 3 (overall range: 24% vs 21%) with more of a continuum between groups. The positive correlation was also significant between $T_{re}$ and %BF for the uphill stages, which differs with results from Weller et al. (1997) observing the correlation at 30% $\dot{V}O_{2,\text{max}}$ in a 5°C environment and not at 60% $\dot{V}O_{2,\text{max}}$. Their range of %BF was however narrower than in our study (15% vs 24%).

All our correlations were also true for the sum of 7 skinfolds as this factor was integrated in the calculation of %BF. This finding adds some evidence in favour of a role of subcutaneous fat on overall thermoregulatory parameters during exercise in cool conditions, similar to what was observed in the heat (Havenith et al., 1990a; Havenith et al., 1998) and in cool conditions (Havenith et al.,1998). It is however very difficult to match males and females for anthropometry and physical fitness at
the same time as indicated by Havenith (2001a), fat content being often cofounded with physical fitness (Havenith *et al.*, 1990b).

- Females showed greater sensitivity to changes in external factors (air velocity and low exercise intensity) compared to males. Correlations exist between thermoregulatory parameters and %BF (or sum of skinfolds) during positive work and resting phases. This may explain the origins of sex differences during clothed exercise in cold air.

### 6.4.1.2. Regional skin temperature responses

To our knowledge, our investigation was the first to use a whole-body mapping approach for clothed participants during exercise. Frim *et al.* (1990) also used infrared thermography on a group of five males but this was limited to the torso region and measurements were performed after a resting cold exposure.

The main SEX differences in regional $T_{sk}$ were observed in the upper and lower limbs especially at ASCENT 2 with almost no differences at DESCENT. The average regional $T_{sk}$ difference between males and females was indeed the highest at ASCENT 2 ($T_{sk,local}$ 1°C higher for males). In contrast, for the running study (Chapter 3), this average regional $T_{sk}$ difference was larger between sexes ($T_{sk,local}$ 2°C higher in males) in a semi-nude condition and continuously exposed to a 2.8 km.h$^{-1}$ air velocity.

From skinfold assessment in the present experiment, correlation analysis revealed a negative relationship between thigh $T_{sk}$ and thigh skinfold thickness with both groups combined ($r = -0.69$, $p<0.01$) though this may have been artificially created by the large difference in thigh skinfold between sexes. Subcutaneous fat may partly account for sex differences in the lower limb region (and potentially in the hip region) but other factors such as blood flow redistribution and segment geometry may explain the discrepancy in other regions.

In the literature, regional $T_{sk}$ values have only been reported during hill walking (6 males) by Pugh (1966, 1967, 1969) over 7 body segments (from up to 14 regional contact measurements) in the context of negative heat storage. His results gave important insights into the influence of clothing worn during “Four Inns Walk” to explain casualties of the 1964 event. With wet clothing and wind, $T_{sk}$ of the lower limbs fell to 14°C emphasizing the lack of insulation and protection from wind and wetting of the trousers (Pugh, 1966). The lowest regional $T_{sk}$ values in our
experiment were found at the palmar hands at PRE (25°C) and anterior arms at ASCENT 2 (25°C) for both males and females. In our experiment, with positive heat storage in the first phases, the exposure of the arms after ASCENT 1 (removal of the fleece layer) was beneficial for heat loss especially due to the specific geometry of the arms.

Two groups of body segments could be distinguished from their dynamics of $T_{sk}$ throughout the protocol. On one hand, the torso regions (chest, abdomen, upper back) displayed a progressive $T_{sk}$ fall over the ascent in opposing way as $T_{re}$, and remained constant during wind exposure. On the other hand the remaining regions (extremities, lower limbs) increased concurrently with $T_{re}$ during the ascent and fell after CHILL exposure. As expected, the loss and recovery of insulation over the torso (fleece top) contributed largely to the changes in $T_{sk}$ for torso regions. It was clear that the fleece was sufficient to maintain $T_{sk}$ with added frontal air velocity at CHILL. For extremities (hands, face) and lower limbs, muscle heat production during positive work was important to promote peripheral cutaneous vasodilation already at ASCENT 1, as can be inferred from the large increase in palmar hand $T_{sk}$ (+4.5°C on average). From CHILL to DESCENT (downhill phase), all regions exhibited a significant increase in $T_{sk,local}$.

Although the range of $T_{sk}$ was comprised between 25°C and 31°C for both sexes, our results highlighted sex differences in the $T_{sk}$ dynamics, with $T_{sk}$ changes being more pronounced in all body regions for females except for the legs. As an example, anterior arms $T_{sk}$ fell by 2.9°C from PRE to ASCENT 2 for females as opposed to 2.1°C for males. Abdomen $T_{sk}$ increased by 2.4°C from CHILL to DESCENT for females as opposed to 1.8°C for males.

This enhanced magnitude of changes for females could be explained by a combination of a better ability to redistribute regional blood flow (Graham, 1988) and geometrical specificities due to the larger area-to-mass ratio for females (for the whole-body and body segments). In the passive upper limbs involved in the arm swing, heat loss may be favoured with a large surface area and a small mass, as found in females with the stronger arm cooling. In the active lower limbs, the increase in $T_{sk}$ is larger for males as can be expected from the combination of higher heat production and lower tissue insulation provided by subcutaneous fat compared to females.
Group-average body maps of relative $T_{sk}$ over the five stages revealed very similar $T_{sk}$ distribution between males and females. Some topographical consistencies were clearly highlighted for the present clothed conditions in line with findings on unclothed participants:

- upper body was warmer than the lower body, with the importance of active lower leg muscles on surface $T_{sk}$
- a V or Y-shape of colder $T_{sk}$ was observed over the anterior torso
- on the face, the colder nose and cheeks as opposed to the warmer orbital crease
- strong contrast between body regions during exercise as opposed to the more homogeneous distribution at rest

Similar to the running exercise, hill walking corresponds to a weight bearing exercise and involves the lower leg musculature. Heat produced within the calves muscle is conveyed to the surface leading to an increase $T_{sk}$ (Cooper et al., 1959) which is clearly visible on the group-averaged body maps. The lower leg $T_{sk}$ remained elevated even during the resting phase with wind exposure.

The distinct anatomical regions forming a cooler Y-shape over the anterior torso were in good agreement with the patterns of the previous chapters. Pectoral and abdominal regions displayed lower $T_{sk}$ than the surrounding shoulder, sternal or suprailiac regions. This was more pronounced when the fleece layer was removed during ASCENT 2.

Some findings about $T_{sk}$ distribution were however specific to this experiment combining clothing insulation and load carriage with a scenario simulating a day-hike:

- the influence of the backpack pressure on $T_{sk}$ in localised body regions (chest, abdomen, upper back, lower back).
- highly homogeneous $T_{sk}$ over the whole torso during the downhill walk
- homogeneous $T_{sk}$ around the extremity joints (elbow crease, popliteal fossa)

The second part of the simulated hike (downhill walking) provided information about exercise at a low intensity whilst $T_{re}$ was decreasing. This decreasing $T_{re}$ also occurred in previous experiments but observations were made only 10 minutes post-exercise. In the present study, infrared measurements were taken 45 minutes (15 minutes of rest followed by 30 minutes at 20% $VO_{2\text{max}}$) after a moderately intense
uphill exercise. Torso $T_{sk}$ was highly uniform except for the pectoral region (breast for females) and reached pre-exercise values. It can be assumed that in both clothed and unclothed experiment, moderate intensity exercise contributes to reinforcing $T_{sk}$ contrasts between body regions and this phenomenon is reversed during passive recovery (chapter 3 and 5) or reduced exercise intensity (present study).

- During the simulated hike, females exhibited lower regional $T_{sk}$ compared to males in a limited number of localised regions (upper and lower limbs). Regional $T_{sk}$ remained within the comfort range compared to more extreme hiking protocols. No sex differences were found in patterns of $T_{sk}$ distribution, exhibiting consistent features in good agreement with those observed during unclothed experiments.

**6.4.1.3. Overall and regional perceptual responses**

No sex differences were found on overall perceptual responses ($TS_{overall}$, $WS_{overall}$ and $TC_{overall}$) considering the entire protocol. At PRE, females exhibited a lower $TS_{overall}$ compared to males (*cold vs slightly cool*). This was recorded 5 minutes after entering the 5°C climatic chamber and generally agrees with Karjalainen (2012) reporting that females feel cooler than males in cool conditions at rest based on a meta-analysis of laboratory and field studies. They also indicated larger dissatisfaction for females in cool environments which closely relate to the tendency for lower $TC_{overall}$ ($p=0.13$) for females compared to males at PRE. At this stage $\bar{T}_{st}$ was similar between groups but regional $T_{sk}$ in the face and limbs was lower for females and may have contributed to this perceptual discrepancy. Despite the regional $T_{sk}$ differences, there was no difference in $TS_{local}$.

During the simulated hike, females reported a lower $WS_{overall}$ than males at ASCENT 1 (wearing T-shirt, fleece and backpack) whereas the sensation was similar at ASCENT 2 (*wet*). The difference in moisture sensation may have several underlying determinants. It is well established that females have a higher $T_{core}$ threshold for sweating and this may have delayed the onset of sweating (Cunningham, 1978). The onset as well as the amount of sweating may have been different as the exercise was performed at a fixed $\%VO_{2,max}$, eliciting lower rate of absolute metabolic heat production and lower sweat rates for females (Gagnon *et al.*, 2008). Sweat rate was however not measured at the different stages to confirm this hypothesis, though on average a 15% lower value was observed for females ($p=0.21$).
At ASCENT 1, males perceived their armpits wetter than females. The accumulation of non-thermal sweat in this region with limited evaporative capability may have in part driven the overall sensation for males.

$WS_{local}$ was different between sexes at ASCENT 2, but again this was limited to a single body region: the face. From sweating body maps obtained during running exercise (Smith and Havenith, 2011), it appears that the face is a region with very high sweat production similar to central back ($700 \text{ g.m}^{-2}\text{.h}^{-1}$ at 55% $\dot{V}O_{2,max}$), though data for females at the face are not known. The face appears to be a very specific region in this protocol as we observed that face $T_{sk}$ was positively correlated with $TS_{local}$ and interestingly with $TS_{overall}$ for most protocol stages. The relative importance of the face for perception has also been found by others, notably with cooling or heating interventions (Armada da Silva et al., 2004, Cotter and Taylor, 2005; Schlader et al., 2011). This region could then be targeted with improved insulation and/or heat dissipation in order to maintain optimal $T_{sk}$ and avoid extreme sensations.

The last specific sex difference in perceptual responses occurred during the forced wind exposure. Females tended to be more affected than males by air velocity as they reported lower $T_{C_{overall}}$ votes at CHILL despite no differences in $TS_{overall}$ and $WS_{overall}$. It can be hypothesized that the drying action of this convective flow may have been felt more pleasant for males (with an hypothetical wetter face), or it might be a stronger sensitivity to air velocity for females as reported by several studies (Karjalainen, 2012).

In terms of perceptual responses, it is noteworthy that RPE was similar between males and females despite the higher HR for females during the ascent (+20 bpm). This finding is in agreement with Stevens et al. (1979) who reported a lowered HR for males during cold air exercise compared to neutral environment whereas females maintained a similar heart rate in cold and neutral environments.

In summary, there were a very limited number of SEX differences in overall or regional perceptual responses suggesting that the simulated hike in these controlled cool conditions led to similar thermal and effort perceptions. Yet, wearing an identical clothing ensemble for both males and females resulted in different thermoregulatory and cardiovascular strain between sexes. As the various stages of
the protocol were standardised for duration and conditions (clothing, activity), it is difficult to extrapolate the results into a proper real-life scenario where personal behavioural adjustments would have taken place. In a field study setting, Pugh (1969) reported that groups of hill walkers had different clothing strategy throughout the self pace 45-km walk. The fastest pair “did not wear hats” and “exposed their forearms and legs by rolling up their sleeves and trousers”. This type of behavioural thermoregulation can be very efficient and is in good connection with the intensity of exercise and the need of heat dissipation.

- Only minimal overall and regional perceptual differences were found between sexes throughout the simulated hike despite the reported thermoregulatory and cardiovascular differences. Females appeared to be more prone to discomfort during the inactive phases of the hike.

6.4.2. The influence of wearing a backpack during a simulated hike

Most of the research investigating loaded vs unloaded walking was either focused on heavy load carriage by military forces or school bags worn by children and adolescents, with a primary interest in metabolic and biomechanical parameters (energy expenditure, trunk flexion, EMG etc.). To our knowledge, no protocol has attempted to match the physical demand in the loaded and unloaded conditions. Some studies were focused on the influence of increasing load mass on these parameters and therefore exploring loaded and unloaded tests similar to our conditions (using pre-pubertal populations). Results indicated that changes in kinematics, EMG and discomfort were limited between 0% and 10% body mass load but became significant over 10% of body mass (Bauer et al. 2009, Devroey et al. 2007). The thermal strain induced by any additional equipment has been overlooked with the exception of two studies (Vrijkotte et al., 1992; Majumdar et al., 1997).

6.4.2.1. Overall thermoregulatory responses

The absence of significant differences between the load and no load conditions on $T_{re}$ and HR responses indicated that the workload was adequately adjusted between the two sessions. There was also no overall effect of wearing a backpack on $\bar{T}_{sk}$ although specific differences were observed during ASCENT1 and ASCENT2 ($\bar{T}_{sk}$ 0.6°C higher with backpack). Majumdar et al. (1997) used the same stepping exercise for 40 minutes in a 34°C environment with and without body armour (20% body mass)
and found a 0.3°C higher $\bar{T}_{sk}$ with body armour after 30 and 40 minutes of light exercise. More surface areas were covered (chest and back) with their body armour compared to our study (mainly the back). It can however be assumed that $T_{sk}$ was more homogeneous with and without body armour in their case due to the stronger environmental strain. They did not report $T_{core}$ values.

In our experiment, $\bar{T}_{sk}$ significantly decreased from PRE to ASCENT 2 (-0.5°C) for males without backpack and remained constant for males with a backpack. The absence of restriction for heat dissipation in the back regions may have largely contributed to explain this overall difference. The regional importance of this phenomenon will be discussed in 6.4.2.2. Majumdar et al. (1997) found a progressively larger increase of $\bar{T}_{sk}$ with vs without body armour after 30-40 minutes of exercise (with: +0.7°C vs without: +0.2°C) as could be expected from the environmental and clothing conditions.

During our wind exposure, clothing conditions were exactly similar (no load, 2 layers for the upper-body), it is interesting to note that $\bar{T}_{sk}$ stabilised exactly at the same value, hence showing opposite changes for males without backpack (0.4°C increase in $\bar{T}_{sk}$) and males with backpack previously carried during the ascent (0.2°C decrease in $\bar{T}_{sk}$). It can be implied from this observation that overall insulation is most important when strong convective cooling is applied regardless of the pre-exposure state of the body.

In a similar type of setting, Willems and den Hartog (1996) measured a 2°C drop in $\bar{T}_{sk}$ (from 34°C to 32°C) during a forced after-chill for 30 minutes in a 10°C environment following 30 minutes of exercise but they did not report the wind speed. In our study, the addition of one extra layer of insulation managed to offset the environmental cooling power (2.8 m.s$^{-1}$ wind in 15°C $T_a$), thus limiting the changes in $\bar{T}_{sk}$. This also shows the importance of this type of behavioural adjustment in a real-life scenario. Further investigation would be required to quantify the potential risks of remaining in a situation of low insulation (only T-shirt) on $T_{re}$ and $\bar{T}_{sk}$ during this kind of wind exposure.

During the descent phase, no significant differences were displayed between the load and no load conditions, $\bar{T}_{sk}$ was increasing towards the end whilst $T_{re}$ was decreasing.
in both conditions. Despite the presence of the backpack, $T_{sk}$ reached the same values than without a backpack at this low-intensity exercise. It can be speculated that a global redistribution of heat occurred during negative work with a lower metabolic demand. Wearing a backpack was of little importance for heat dissipation in a situation with slow body motion and limited pumping effect except in the lower back (Figure 6.12).

- Wearing a backpack did not significantly influence $T_{re}$ highlighting that workload was well adjusted between the load and no load conditions. It did however contribute to a higher $T_{sk}$ during high-intensity exercise but it had no influence during neither low-intensity exercise nor resting phases.

### 6.4.2.2. Regional skin temperature responses

Differences in regional $T_{sk}$ were limited to the regions covered by the backpack as could be expected. Significant $T_{sk}$ differences were mainly found in the back, most importantly in the lower back, as well as in the pectoral/clavicular regions (under the shoulder straps) and the abdominal regions (under the waist belt). Differences varied from 1°C to up to 3°C mainly during the uphill stage with almost no differences at PRE and CHILL in the same clothing ensemble (no backpack). The discrepancy caused by wearing a backpack can be seen in close agreement with the 3°C increase in chest $T_{sk}$ (contact measurement) observed by Vrijkotte et al. (1992) looking at the effect of wearing a ballistic vest as compared to no vest over a wide range of environmental conditions. No information was provided about the back region.

In a study examining the influence of clothing on torso $T_{sk}$ measured by infrared thermography, Livingstone et al. (1988) compared mean torso $T_{sk}$ (2 contact points at the nipple and navel) in different clothing ensemble after 60 minutes of resting in a 5°C room. They obtained a 3°C difference in mean torso $T_{sk}$ in a single uniform layer of clothing compared to three uniform layers of clothing (coverall made of knitted pile fabric).

A specific analysis of discrete body regions covered by the backpack (Figure 6.12) gave a finer representation of the relative importance of the load and its pressure onto the clothing layers regardless of the predefined body segmentation (introduced in Chapter 2). The region of the lower back was consistently highly impacted (3°C higher than no load) and its influence on $T_{sk}$ even persisted 15 minutes after wind
exposure. In the anterior torso, $T_{sk}$ became highly homogenous at DESCENT so that the conditions could not be distinguished on the $T_{sk}$ body maps (Figure 6.11).

The presence or absence of backpack helped to even more precisely define the normal $T_{sk}$ patterns under clothing. It was clear from the resting phases (with no backpack) and all stages in the no load condition that a consistent V-shape of colder $T_{sk}$ was displayed in the anterior torso (pectoral and abdominal regions), together with a T-shape of warmer $T_{sk}$ over the sternal region and a T-shape region over the posterior torso.

Wearing a backpack reinforced the V and T-shapes over the anterior torso with warmer shoulder and hip regions. A specific pattern was revealed in the posterior torso, similar to an X-shape with a long middle portion corresponding to warm $T_{sk}$ over the spinal cord.

- Wearing a backpack significantly influenced regional $T_{sk}$ during the exercising phases and the impact was limited to the regions where pads are in contact with the skin, especially the lower back. Consistent features of the normal $T_{sk}$ patterns under clothing have been described regardless of the load condition.

6.4.2.3. **Overall and regional perceptual responses**

The influence of wearing a backpack on overall perceptual responses appeared almost exclusively during the first phase of the ascent. Participants felt warmer, wetter and tended to be in state of stronger discomfort (1 scale unit for all ratings) whilst wearing a backpack compared to no backpack at ASCENT 1. This was associated with warmer $T_{S_{local}}$ on the lower back, worse $T_{C_{local}}$ over the abdomen, lower back and upper back (1 to 3 scale units difference).

In the literature, the investigation from Vrijkotte et al. (1992) was the only one to report perceptual responses whilst wearing a vest or no vest. After 30 minutes of moderately hard walking in a 15°C environment, their 73 males rated $T_{S_{overall}}$ slightly warmer (0.5 scale unit) and overall wetness sensation was similar (between neutral and slightly wet) with vest compared with no vest. $T_{S_{local}}$ and $W_{S_{local}}$ were 1 scale unit (on a 7-point scale) higher for the vest condition (Vrijkotte et al., 1992).

It can be hypothesized that the threshold for sweating had been reached in the first 30 minutes of the protocol and the limited evaporative cooling under the backpack was
detrimental for thermal perceptions with increasing $T_{sk}$ and potential sweat accumulation in contact with the skin.

At the end of the uphill stage (ASCENT 2), local differences were particularly observed on the lower back with warmer $T_{S_{local}}$ higher $W_{S_{local}}$ leading to reduced $T_{C_{local}}$ for the backpack condition. The contact with wet fabric may again represent the underlying mechanism for this warm discomfort (Gagge et al., 1969).

Lastly, an overall difference was found at DESCENT for $W_{S_{overall}}$ being significantly higher for the backpack condition. This was associated with wetter armpits as well as warmer lower back and abdomen and greater discomfort at the lower and upper back.

Over the protocol, it would be erroneous to establish causal relationships between local and overall perceptual responses. The large inter-individual variability in the responses may have obscured some similarities or differences. A larger sample size or similar results with another population would be required to confirm the regional contribution of certain body regions to overall thermal votes (Pellerin et al., 2004).

- Wearing a backpack influenced overall and regional $T_{sk}$ to a limited extent specifically during the inactive phases of the protocol. Locally, the main affected region was the lower back region with 3°C higher $T_{sk}$ with backpack. The perceptual strain placed on the participants without backpack was lower than that for the loaded participants as indicated by lower thermal and wetness sensations during the ascent.

6.5. CONCLUSIONS

The findings of the present study offer descriptive information on overall and regional thermoregulatory and perceptual responses in a specific scenario. The different stages of this scenario were analysed with special attention to potential SEX differences together with a comparison between the presence or absence of BACKPACK in the male group.

- SEX differences were highlighted in the present hiking protocol with 0.3°C higher $T_{re}$, 0.6°C lower $T_{at}$ for females compared to males in all stages from the start except for the downhill phase of the protocol. Females were more
responsive to air velocity and low-intensity exercise leading to larger changes in thermoregulatory responses. Our results provide some evidence that %BF was associated with thermoregulatory responses during the ascent. Regional Tsk were different between sexes only in the upper and lower limbs (lower for females), especially at the end of the uphill stage. The relative Tsk maps demonstrated the similar Tsk distribution between sexes and this was consistent over the different stages. The clothed pattern in the hiking conditions displayed more consistencies between sexes than the nude pattern in running conditions (Chapter 3).

- **SEX** only little affected thermal perceptions with the most notable differences displayed during the inactive stages. Females reported more cold discomfort either before hill walking or during wind exposure. Despite the consistent but small regional Tsk differences between sexes, the local thermal votes almost did not differ. The most important region in the generation of cold and warm discomfort was the face together with the lower back and armpits for warm discomfort. Moreover face Tsk correlates with overall sensation which suggest that local interventions at the face could be efficient for the maintenance of thermal comfort.

- **WEARING A BACKPACK** significantly influenced thermoregulatory and perceptual responses during the uphill stages of the protocol. WEARING A BACKPACK induced a 0.6°C higher Tsk with a strong local influence in the regions covered by the backpack, increasing regional Tsk by up to 3°C (lower back), inducing wetter and warmer sensations (armpits, back) and greater local discomfort. Overall thermal votes reached high levels more rapidly whilst WEARING A BACKPACK but ended at similar levels than the no backpack condition at the end of the ascent and the remaining stages of the protocol.

The investigation of recreational hill walking in non-adverse environment is relatively unique, or at least has never been reported in the literature. Regarding the populations involved in this popular type of outdoor activity, the investigation of two main factors (SEX and BACKPACK) together with the fine body-mapping approach added some important value.
Some practical information is relevant to clothing design and will be discussed more thoroughly in Chapter 9. The main practical findings reinforced intuitions and classical issues faced by hikers, they are now documented with a quantitative analysis.

- Females require higher levels of insulation when they are exposed to sudden changes in environmental factors (reduced $T_a$ or increase air velocity). There is a clear need for adaptative clothing solutions that can facilitate behavioural thermoregulation by adding layers of insulation with ease, limited bulk and efficiency (quick break, sudden gust etc.)

- When both males and females are exercising at moderately intense workload, they are facing the same thermal issues with the same magnitude. There is no need to specify different clothing requirements, though adjusting clothing fit for the specific morphology of both sexes is still crucial. Moreover, it seems clear that the tested clothing ensembles are fairly adequate to the experimental conditions, as only moderate discomfort was experienced.

- Protection of the face seems crucial as face $T_{sk}$ correlates with overall sensation and face in general contributes to cold and warm discomfort. This implies that this exposed region should be specifically targeted within the clothing ensemble through adaptative insulation or improved heat dissipation depending on the activity.

- Solutions helping to reduce the accumulation of sweat in contact with the skin may be helpful (in the complex between skin / clothing / backpack) but our results demonstrate that discomfort appears regardless of the presence of a backpack after more than 30 minutes of exercise.

- Adaptative clothing solutions, i.e clothing that can vary in their thermal properties or coverage, can be beneficial for everyone as changes in terrain and environmental parameters may vary widely over a limited time frame. The need for adequate heat dissipation during periods of high exercise-intensity or high environmental strain is crucial as excessive increases in body heat content may represent a danger in the opposite direction during periods of inactivity or limited activity. An adaptative concept has been developed from these requirements and will be presented in Chapter 9.
CHAPTER 7

Modifications of regional skin temperatures by uniform and non-uniform clothing distribution whilst running at 5°C

Chapter Summary

This chapter presents a clothing intervention with running ensembles whose insulation distribution was based on skin temperature patterns observed in a previous study. The goal was to modify regional skin temperatures and their uniformity across the body in order to modify thermal perceptions during a 40-min running bout at 70% $\dot{V}O_{2,\text{max}}$. This was performed with ensembles insulating heavily warm body regions (WBRI) or cold body regions (CBRI) and with an existing control ensemble with uniformly distributed insulation (UDI). Thermoregulatory responses of the twelve male participants were not affected by the type of clothing (similar rectal temperature and mean skin temperature) nor were heart rate or rate of perceived exertion. Skin temperature distribution was strongly impacted, highlighting very heterogeneous temperatures (WBRI), a natural distribution of temperatures (UDI) and relatively homogeneous temperatures (CBRI). This intervention also confirmed the existence of classical features in the skin temperature patterns (Y-shapes, warmer creases, colder lower body). Different skin temperature distributions led to small differences in overall and regional perceptions. It was yet found that targeting the naturally cold regions with higher insulation (CBRI) provided a comfort advantage during rest and exercise in the cold but this would need to be further confirmed with less strenuous activity and/or colder exposure.

Context

The previous chapter investigating the thermal responses during a typical hiking scenario was focused on the interaction of several $T_{sk}$ determinants in an ecological situation close to real-life conditions. Variations of external determinants were introduced in the protocol with the increase of AIR TEMPERATURE, the adjustments of CLOTHING according to the scenario and the addition of AIR...
VELOCITY during the exercise after-chill. Furthermore, METABOLIC HEAT PRODUCTION, an internal determinant, was also modified during the protocol with moderate intensity during uphill walking and low intensity exercise during downhill walking.

The present study was designed fixing the large majority of external and internal determinants allowing to focus on the effect of CLOTHING, specifically the distribution of INSULATION within the clothing ensemble. It was aimed towards manipulating $T_{sk}$ and more importantly the distribution of $T_{sk}$ across the body. Nielsen and Nielsen (1984) indeed stated that the change in $T_{sk}$ distribution will depend on the location of the clothing insulation over the body surface. This intervention on CLOTHING design to be used in this study was only made possible by the knowledge of $T_{sk}$ distribution obtained from the mapping technique developed in the present work. In previous chapters, the natural distribution of $T_{sk}$ across the body was determined in various semi-nude conditions: running (Chapter 3), at rest and during cycling (Chapter 4) and rowing (Chapter 5). As a next step, it was judged interesting to manipulate this natural $T_{sk}$ distribution in order to improve thermal comfort compared to a normal clothing condition in the specific context of exercise in the CBRI. The manipulation was performed using two different approaches aimed at controlling heat dissipation from the skin. This intervention created a connection between descriptive knowledge and practical consequences for industrial design.

7.1. Introduction

Clothing acts as a barrier for heat and moisture transport between the skin and the environment. The presence of the layer of insulation on the skin interferes with the heat exchanges at the surface and therefore implies modifications of $T_{sk}$ and its distribution. It is largely recognized that $T_{sk}$ is not uniform over the body, even in a state of thermal comfort (Olesen and Fanger, 1973) and the range of $T_{sk}$ variation increases as ambient temperature decreases (Werner et al., 1985).

In cold environments, autonomic thermoregulation triggers heat-conservation mechanisms such as vasoconstriction to help the body maintaining thermal balance. This change in the vasomotor tone occurs rapidly in response to an external cold challenge. By limiting or suppressing the arrival of warm blood from the core, this induces a drop in surface temperature especially in the extremities. The use of clothing corresponds to another type of thermoregulation which can be referred to as
behavioural thermoregulation. An extra layer of insulation can reduce the heat losses over the whole body. In temperate countries, people commonly choose their clothing according to the outside temperature. In cold seasons or at night, they often create a non-uniform distribution of clothing insulation by wearing multiple layers, most of the time protecting more the upper body (shirt, jumper, and jacket). This behaviour seems to go hand in hand with physiological thermoregulation which aims at maintaining the thermal balance, protecting the vital core organs in the trunk. However, in the context of exercise, the majority of sports garments are composed of a uniform single layer even in cold conditions.

Although extensive research has been carried out to explore the possible benefits of newly developed synthetic fibres in the last thirty years, only few researchers have investigated the role of different configurations of clothing. Clothing configuration or construction can be split into two categories:

- clothing with uneven coverage (partial vs full)
- clothing with uneven distribution of insulation (extra insulation targeting specific regions)

Studies performed at Nara women’s University in Japan have highlighted the importance of the counter-current heat exchange when half of the limbs were not covered (Jeong et al., 1988, 1989, 1990, 1993, Lee and Tokura, 1998). Partial coverage therefore induces a better maintenance of core temperature in the cold, this is however counterbalanced with obvious local discomfort of the exposed body regions. Also using partial clothing coverage, Hanada et al. (1982) used a combination of exposed areas and found that different sensation can occur with similar overall insulation and similar $\overline{T}_{sk}$.

Only a few experiments have looked at the effect of a non-uniform distribution of clothing insulation. In this category of clothing configuration, the ensembles to be compared covered the same body surface. Clothing insulation was either distributed on the limbs or the trunk (Nielsen and Nielsen, 1984) or differently on the upper and lower body (Lee et al., 1993; Kim et al., 2008). A study by Sari and Candas (2000) combined the 2 approaches with partial coverage and high insulation compared with full coverage and light insulation. Overall, it can be concluded that non-uniform
clothing insulation induced a different $T_{sk}$ distribution, different $\overline{T}_{sk}$ but with no impact on subjective responses.

The initial idea of the present study was to manipulate $T_{sk}$ distribution with limited change in $\overline{T}_{sk}$ by means of three different distributions of clothing insulation. A commercially available clothing ensemble with uniform insulation was used. Moreover, two ensembles were designed according to $T_{sk}$ patterns obtained in a previous clothed experiment. $T_{sk}$ maps allow the definition of clear cold and warm regions within body segments. Unlike the other studies looking at non-uniform clothing insulation, the created ensembles provided intra-segmental variations in insulation. Havenith et al. (2008b) suggested that covering the specific cold regions would benefit the overall comfort while targeting the warm regions would prevent heat losses. Targeting specific regions would also either maximise or minimise the uniformity of $T_{sk}$ across the body. $T_{sk}$ uniformity can be defined as the within-subject variability of $T_{sk}$ around an average value, i.e the standard deviation of $T_{sk,local}$ across the body. The purpose of the study was therefore to understand the thermal responses and possible improvement in comfort induced by clothing targeting cold or warm regions with extra insulation, but similar overall insulation.

It was hypothesized that:

- the different clothing ensembles will produce three different types of $T_{sk}$ distribution with limited change in $\overline{T}_{sk}$
- the non-uniformity of $T_{sk}$ will be larger in the ensemble targeting warm regions with extra insulation compared to the one targeting cold regions
- clothing targeting the warm regions will induce a larger increase in body heat content because it will impede heat loss
- local thermal perception will be directly linked to the local $T_{sk}$
- overall thermal comfort will be improved in the clothing targeting the cold regions

In addition to these main hypotheses, the datasets obtained will also allow the comparison of nude (Chapter 3, 4 and 5) and clothed body-mapping in similar conditions. An analysis could be performed in order to bring some insights into the role of CLOTHING per se on the $T_{sk}$ patterns. The role of AIR VELOCITY, another external determinant of $T_{sk}$, will also be discussed based on the data obtained in this chapter.
7.2. Methods

7.2.1. Participants
Twelve Caucasian males, all physically active, were recruited among the student population of Loughborough University with various exercise background (football, hockey, running). They all signed an informed consent after explanation of the study methods and goals. All participants completed a pre-test session and three experimental session each separated by one week. The experimental sessions were performed the same day, at the same time of day to prevent circadian effects, though different participants were tested at different times and therefore inter-individual variations in circadian thermal status was not controlled.

7.2.2. Pre-Test session
The pre-test session involved anthropometric measurements of height and body mass. Skinfold thickness measurements using a Harpenden caliper were performed at 24 sites across the right side of the body for and four sites were used for the calculation of body density (Jackson and Pollock, 1978) and then converted into % body fat using Siri’s equation (1956).

The second part of the pre-test session consisted of a sub-maximal fitness test on the treadmill (h/p cosmos mercury 4.0, Nussdorf-Traunstein, Germany). The test was designed following the guidelines of ACSM (2004) using a ramp test with 4*5 min increments in speed (1.5 km.h\(^{-1}\)) on the treadmill. Maximal fitness level (\(\dot{V}O_{2,\text{max}}\)) was calculated based on Epstein et al. (1999). During the three experimental sessions, a relative workload of 70%\(\dot{V}O_{2,\text{max}}\) was chosen to mimic real life conditions for a training session of regular runners. Participants were familiarised with the subjective evaluation scales (thermal sensation, thermal comfort, RPE) during the first stages of the submaximal test. Scales corresponded to the ones used for the generic skin temperature mapping protocol (cf 2.4.7).

7.2.3. Methodology

7.2.3.1. Clothing
The main purpose of the present study was to modify T\(_{sk}\) distribution by means of clothing with different distribution of insulation. As a first step, a series of tests were
performed in a clothed condition with uniform insulation (Isolate 4000, running top and tights, headband and gloves, Kalenji, France) using the same protocol as presented in Chapter 3. $T_{sk}$ patterns were obtained at the end of 4 specific stages: 5 minutes of rest, 10 minutes of running at $70\% \dot{VO}_{2,max}$, 30 minutes of running at $70\% \dot{VO}_{2,max}$, 10 minutes of post-exercise recovery standing. Environmental conditions were fixed at 5°C, 50% rh with frontal wind at 2.8 m.s$^{-1}$ (resting phases) and 5 m.s$^{-1}$ (exercising phases), sufficient to induce moderate cold discomfort throughout the trial. The $T_{sk}$ body maps of the four different stages were averaged over participants and a final relative body map was computed representing all stages (Figure 7.1). This body map was representative of the $T_{sk}$ patterns over the whole protocol and displayed a clear split between “colder” (relative $T_{sk}$ <1) and “warmer” regions (relative $T_{sk}$ >1).

![Figure 7.1](image)

Figure 7.1 Maps of $T_{sk}$ relative to the group-mean value (anterior and posterior) computed from body maps of 12 males from 4 stages of a running protocol (5°C, 70% RH, 5’ rest with 2.8 m.s$^{-1}$, 10’ running and 30’ running at $70\% \dot{VO}_{2,max}$ with 5 m.s$^{-1}$, 10’ post-exercise recovery standing with 2.8 m.s$^{-1}$). The clothing ensemble worn was Isolate 4000 running top and tights, headband and gloves. Dark red colours correspond to values under mean $T_{sk}$ whereas light yellow colours correspond to values above mean $T_{sk}$. The distinction between areas induced the choice of distribution design.

A selection of two different fabrics was done regarding the choice of the type of insulation. The fabrics were then differently integrated in the creation of two specific prototypes.

The fabrics used are reported in Table 7.1, they were selected to magnify insulation contrasts between body regions based on a reference which was the fabric used for
the Isolate 4000 ensemble (Super Roubaix). In the available fabric range, changing
the thermal resistance was inevitably linked to modifications of other thermal
properties of the fabric such as air permeability and vapour resistance.

<table>
<thead>
<tr>
<th>Table 7.1</th>
<th>Thermal characteristics of the 2 fabrics selected for the prototypes (targeting cold and warm regions) and the fabric from the Isolate 4000 (Super Roubaix).</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>« Equarea »</td>
</tr>
<tr>
<td>Thermal resistance (m².K.W⁻¹)</td>
<td>0.020</td>
</tr>
<tr>
<td>Vapour resistance (m².Pa.W⁻¹)</td>
<td>1.76</td>
</tr>
<tr>
<td>Thickness (no pressure)</td>
<td>0.80</td>
</tr>
<tr>
<td>Air permeability (L.m².s)</td>
<td>2200</td>
</tr>
</tbody>
</table>

Using these fabrics the ensembles were designed as follows:

**Clothing “CBRI” (Cold Body Regions Insulation) or “C”** corresponded to a full
ensemble (running top and tights) where a double layer of insulation (“Double Super
Roubaix”) was targeting the regions with “colder” T_{sk} based on the average body
map (Figure 7.1). In contrast, the low insulated areas were the regions with naturally
“warmer” T_{sk}, on which thinner fabric was used (“Equarea”).

**Clothing “WBRI” (Warm Body Regions Insulation) or “W”** was the exact mirror
from clothing CBRI with high insulation over the “warmer” regions and low
insulation over the “colder” regions.

The prototypes CBRI and WBRI were manufactured within the Decathlon Industrial
Prototyping Services in a Medium size with the same patterns and dimensions of the
Isolate 4000.

The clothing ensembles were compared with **Clothing “UDI” (Uniform
Distribution of Insulation) or “U”**, a commercially available ensemble named
Isolate 4000 (Kalenji, Decathlon, France) having a uniform distribution of clothing
insulation (same Super Roubaix fabric all over).
For clothing CBRI and clothing WBRI, the surface area covered by the high and low insulation fabrics was identical. The prototypes were made black so that the differences between fabrics were hardly noticeable. A black version of clothing UDI (Isolate 4000) was chosen, orange seams were tainted in black and all logos removed. The mass of clothing CBRI and WBRI was higher than that of clothing U, mainly due to the specific mass of the double layer of insulation.

<table>
<thead>
<tr>
<th>Table 7.2 Clothing mass (g) of the dry clothing ensembles</th>
</tr>
</thead>
<tbody>
<tr>
<td>clothing CBRI</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>top</td>
</tr>
<tr>
<td>tights</td>
</tr>
<tr>
<td>total</td>
</tr>
</tbody>
</table>

### 7.2.3.2. Protocol

The experimental protocol was following the same chronology as presented in Chapter 3 (Figure 7.3). The protocol was designed to reproduce the different stages of a typical running scenario. Four different sets of infrared measurements were taken with the subject standing in an anatomical position at the end of each stage: before running, 5 minutes after entering the climatic chamber without air velocity (PRE), after 10 minutes of running at 70% $v_{O_2, max}$ with 2.8 m.s$^{-1}$ (RUN10), after 40
minutes of running at 70% $\dot{V}O_{2\text{max}}$ with 2.8 m.s$^{-1}$ (RUN40) and after 10 minutes of post-exercise recovery standing on the treadmill without air velocity (POST).

![Figure 7.3 Schematic representation of the protocol, Arrows correspond to the 4 stages for administration of the perceptual questionnaires followed by infrared imaging. Participants were standing on the treadmill during the inactive phases before and after the exercise bout.](image)

The infrared camera (Thermacam B2, FLIR Systems Ltd, West Malling, Kent, UK, accuracy ± 2°C, thermal sensitivity ± 0.1°C) was fixed on a tripod with adjustable legs at constant lengths regardless of the participant height. Infrared measurements were taken immediately at the end of each stage in close proximity to the treadmill. Participants were assisted in the quick stripping phase (running top taken off, tights rolled down to the ankle) to allow quick and dry exposure (towel) of the bare skin in 10 seconds. Pilot tests with contact sensors highlighted that the course of $T_{sk}$ variations was modified by less than 0.5°C during the stripping and measurement phase (less than 90 seconds in total) in various body regions. The authors are confident that the $T_{sk}$ patterns closely reflect the patterns that were present underneath the clothing, and this is in line with findings from others (Livingstone et al., 1988). Limitations regarding the exact value for absolute $T_{sk}$ can not be ruled out. However the procedure was standardised and errors should have been consistent throughout all clothed protocols.

Metabolic rate was calculated using indirect calorimetry from measurements of oxygen uptake and carbon dioxide output with a portable breath-by-breath system (MetaMax 3B, Cortex, Germany). Prior to each experimental session The MetaMax was calibrated (atmospheric pressure reading) for volume (3L HansRudolph syringe) and gas concentrations (ambient air and calibration gas of 4.2% CO$_2$, 16.5% O$_2$ and 20.1% Argon). A flexible Hans Rudolph mask was adjusted to the participant’s face during the preparation phase and was worn only during the first 10 minutes of the second period of running. This was done to avoid interference with face $T_{sk}$ and avoid the build-up of moisture within the mask.
A vertical panel of three 50cm diameter fans (JS Humidifiers, Littlhampton, UK) was placed 10 cm away from the front of the treadmill, which corresponds to a distance of 1 meter from the running participant. Air flow was turned on only during the running periods and the air velocity was set to match the average running speed of the participants i.e 2.8 m.s\(^{-1}\). The actual running speed was set according to submaximal test results and corresponded to 70% \(\dot{V}O_{2\text{max}}\) chosen to simulate the training speed of active runners. Regular calibration of air velocity was performed using a hot-wire anemometer (model TSI Alnor 8455, TSI Instruments Ltd, High Wycombe, UK; range 0.125-50m.s\(^{-1}\)) at the chest level (1.3m) on the treadmill. Air flow was turned off before each set of infrared measurements as recommended by Clark and Edholm (1985).

Perceptual scales (thermal sensation, thermal comfort) were attached on both sides of the fans panel close to eye level to facilitate the reading during exercise. The RPE scale was presented in front of the subjects after administration of the thermal scales. Heart rate was monitored using a Polar RS600 monitor (Polar Electro Oy, Kempele, Finland) after RUN10. The heart rate belt was worn for 10 minutes and then removed to avoid changes in the heat exchanges between the skin and the environment due to
the belt. Body mass and clothing mass were recorded upon arrival at the laboratory and immediately after the session using an electronic scale (Mettler Toledo, 150kg, Mettler Toledo, Leicester, UK). Body sweat loss was calculated from weight loss, adjusted for water intake and corrected by respiratory and metabolic mass losses.

**7.2.4. Analysis**

All infrared thermograms were processed using the custom-made MATLAB procedure in order to obtain group-averaged body maps at each phase of the protocol for each clothing condition (CBRI, UDI,WBRI) as well as quantitative $T_{sk}$ data for predefined regions (see Chapter 2). Relative body maps were also produced at each protocol stage for each clothing condition and they reflected the body map relative to the condition mean skin temperature ($\bar{T}_{sk}$) at each stage.

Mean skin temperature ($\bar{T}_{sk}$) was calculated as the average of all the pixels measured on the entire body surface by the 5 different thermograms, except for the covered body parts (groin and feet). Mean body temperature was calculated from the equation: $\bar{T}_{b} = 0.67* T_{re} + 0.33* \bar{T}_{sk}$.

Statistical Analysis was conducted using the SPSS 16.0. A two-way repeated measures ANOVA was used to investigate the main effect of TIME and CLOTHING ENSEMBLE (abbreviation named CLO).

Dependent variables were $T_{re}$, $\bar{T}_{sk}$, $\bar{T}_{b}$ and local $T_{sk}$. Holm-Bonferroni corrections were applied to allow for multiple comparisons when comparing the different body regions investigated. A Pearson-correlation coefficient was obtained following regression analysis between $T_{sk}$ parameters (local and overall) and body fat parameters or perceptual parameters (local and overall).
7.3. Results

7.3.1. Participants

The participants’ characteristics, aerobic fitness level, running speed are presented in Table 7.3.

7.3.2. Skinfold thickness

Skinfold thickness at 24 locations is presented in Table 7.4.

7.3.3. Evolution of thermoregulatory and overall perceptual responses

7.3.3.1. Rectal temperature, mean skin temperature, body sweat loss

This section introduces the main thermoregulatory responses induced by wearing the different clothing types during the running protocol.

For $T_{re}$, $\bar{T}_{sk}$ and $\bar{T}_{b}$, the overall effect of CLO was not significant (p>0.31) whilst the TIME effect was significant (p<0.01) and the interaction TIME*CLO was never found significant (p>0.25).

The average intra-individual variability of $T_{re}$ over the whole protocol was significantly lower for CBRI compared to UDI (37.87 ± 0.36°C vs 37.86 ± 0.43°C, p<0.05) and tended to be lower than WBRI (37.87 ± 0.36°C vs 37.91 ± 0.40°C, p=0.11).

Sweat loss was significantly lower in UDI compared to both CBRI (UDI: 267 ± 72 g.m^-2.h^-1 vs CBRI: 325 ± 85 g.m^-2.h^-1, p<0.01) and WBRI (UDI: 267 ± 72 g.m^-2.h^-1 vs WBRI: 353 ± 120 g.m^-2.h^-1, p<0.01) with no differences between CBRI and WBRI.

The effect of CLO was significant on sweat accumulation in the clothing ensemble. Sweat in WBRI was significantly larger compared to UDI (WBRI: 79 ± 43g vs UDI: 38 ± 22g, p<0.05) with no differences between WBRI and CBRI, UDI and CBRI (CBRI: 53 ± 26g). The significant difference was primarily due to sweat accumulated in the running top, much larger in WBRI (47g for WBRI, 17g CBRI, 12g UDI) but the amount was similar in all other items (headband, gloves, underwear, socks, shoes) except for the tights (8g for CBRI 2g UDI, 3g WBRI).
Table 7.3. Participants’ anthropometric characteristics (mean ± SD and range) and predicted aerobic fitness level for all participants

<table>
<thead>
<tr>
<th>Participant no</th>
<th>Age (yrs)</th>
<th>Height (cm)</th>
<th>Body Mass (kg)</th>
<th>AD (m²)</th>
<th>AD/M (cm².kg⁻¹)</th>
<th>Body fat content (%)</th>
<th>Total sum of skinfolds (mm)</th>
<th>Predicted VO₂max (mL.min⁻¹.kg⁻¹)</th>
<th>Treadmill speed (km.h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>c1</td>
<td>24</td>
<td>184</td>
<td>75.0</td>
<td>1.97</td>
<td>263</td>
<td>13.3</td>
<td>287</td>
<td>54.3</td>
<td>10.4</td>
</tr>
<tr>
<td>c2</td>
<td>21</td>
<td>183</td>
<td>81.9</td>
<td>2.03</td>
<td>248</td>
<td>11.3</td>
<td>244</td>
<td>54.2</td>
<td>10.3</td>
</tr>
<tr>
<td>c3</td>
<td>22</td>
<td>188</td>
<td>75.0</td>
<td>2.00</td>
<td>266</td>
<td>11.3</td>
<td>229</td>
<td>51.9</td>
<td>9.9</td>
</tr>
<tr>
<td>c4</td>
<td>23</td>
<td>188</td>
<td>82.3</td>
<td>2.08</td>
<td>253</td>
<td>11.5</td>
<td>250</td>
<td>53.2</td>
<td>10.1</td>
</tr>
<tr>
<td>c5</td>
<td>18</td>
<td>172</td>
<td>61.4</td>
<td>1.72</td>
<td>280</td>
<td>7.6</td>
<td>196</td>
<td>55.4</td>
<td>10.6</td>
</tr>
<tr>
<td>c6</td>
<td>21</td>
<td>170</td>
<td>65.0</td>
<td>1.75</td>
<td>269</td>
<td>4.9</td>
<td>138</td>
<td>70.4</td>
<td>13.7</td>
</tr>
<tr>
<td>c7</td>
<td>18</td>
<td>194</td>
<td>96.0</td>
<td>2.27</td>
<td>236</td>
<td>18.2</td>
<td>368</td>
<td>47.6</td>
<td>9</td>
</tr>
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<td>c8</td>
<td>24</td>
<td>175</td>
<td>87.7</td>
<td>2.02</td>
<td>231</td>
<td>13.0</td>
<td>274</td>
<td>51.3</td>
<td>9.7</td>
</tr>
<tr>
<td>c9</td>
<td>26</td>
<td>185</td>
<td>80.5</td>
<td>2.03</td>
<td>253</td>
<td>14.6</td>
<td>300</td>
<td>52.7</td>
<td>10</td>
</tr>
<tr>
<td>c10</td>
<td>25</td>
<td>184</td>
<td>83.0</td>
<td>2.05</td>
<td>247</td>
<td>10.8</td>
<td>231</td>
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<td>9.9</td>
</tr>
<tr>
<td>c11</td>
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<td>187</td>
<td>85.6</td>
<td>2.10</td>
<td>246</td>
<td>13.9</td>
<td>276</td>
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<td>c12</td>
<td>22</td>
<td>185</td>
<td>71.9</td>
<td>1.94</td>
<td>269</td>
<td>11.0</td>
<td>225</td>
<td>57.4</td>
<td>11</td>
</tr>
</tbody>
</table>

mean ± SD 22.0 ± 2.6 182.6 ± 7.0 78.8 ± 9.7 2.00 ± 0.15 255 ± 15 11.8 ± 3.4 252 ± 57 54.9 ± 5.6 10.5 ± 1.2

range 18-26 170 - 194 61.4 - 96.0 1.72 - 2.27 231 - 280 4.9 - 18.2 138 - 368 47.6 - 70.4 9 - 13.7

A<sub>Du</sub> = Dubois body surface area; Mass = body mass; A<sub>Du</sub>/M = body surface area-to-mass ratio; V<sub>O₂</sub>max = predicted maximal oxygen uptake from Epstein et al. (1999).

Table 7.4. Skinfold thickness at 24 body sites (mean ± SD and range) for the group

<table>
<thead>
<tr>
<th>SITE</th>
<th>forearm ant.</th>
<th>biceps</th>
<th>shoulder</th>
<th>clavicular</th>
<th>pectoral</th>
<th>chest</th>
<th>nipple</th>
<th>midaxillary</th>
<th>upper abdom. extern oblique</th>
<th>suprailiac</th>
<th>abdominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean ± SD</td>
<td>6.1 ± 1.2</td>
<td>5.4 ± 1.5</td>
<td>7.3 ± 2.4</td>
<td>5.4 ± 1.1</td>
<td>8.6 ± 2.4</td>
<td>7.7 ± 2.0</td>
<td>9.8 ± 2.4</td>
<td>9.0 ± 2.5</td>
<td>14.4 ± 4.6</td>
<td>10.2 ± 3.8</td>
<td>17.6 ± 6.8</td>
</tr>
<tr>
<td>range</td>
<td>3.6 - 7.3</td>
<td>3.4 - 7.7</td>
<td>4.0 - 11.9</td>
<td>4.0 - 7.4</td>
<td>4.7 - 12.8</td>
<td>5.0 - 11.3</td>
<td>6.1 - 14.7</td>
<td>5.0 - 13.4</td>
<td>6.3 - 23.6</td>
<td>4.5 - 17.8</td>
<td>6.0 - 33.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SITE</th>
<th>thigh</th>
<th>suprapatellar</th>
<th>calf</th>
<th>forearm post.</th>
<th>triceps</th>
<th>neck</th>
<th>suprascapular</th>
<th>scapular</th>
<th>subscapular</th>
<th>infrascapular</th>
<th>lumbar</th>
<th>lumbosacral</th>
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<tbody>
<tr>
<td>mean ± SD</td>
<td>13.9 ± 3.9</td>
<td>6.5 ± 1.9</td>
<td>12.7 ± 4.0</td>
<td>5.3 ± 1.1</td>
<td>10.8 ± 2.9</td>
<td>11.4 ± 1.6</td>
<td>10.9 ± 2.5</td>
<td>11.6 ± 2.5</td>
<td>11.4 ± 2.8</td>
<td>11.6 ± 2.4</td>
<td>14.2 ± 4.3</td>
<td>12.4 ± 3.9</td>
</tr>
<tr>
<td>range</td>
<td>7.3 - 21.3</td>
<td>4.4 - 9.4</td>
<td>4.5 - 17.8</td>
<td>3.5 - 7.3</td>
<td>7.0 - 15.9</td>
<td>8.9 - 13.8</td>
<td>8.0 - 15.5</td>
<td>8.1 - 16.2</td>
<td>6.6 - 16.8</td>
<td>6.5 - 15.5</td>
<td>6.9 - 21.3</td>
<td>5.7 - 19.0</td>
</tr>
</tbody>
</table>
Figure 7.5: Evolution of rectal temperature ($T_{re}$) and mean skin temperature ($T_{sk}$) for the group of 12 males in 3 different clothing conditions during the same running scenario (rest, exercise, post-exercise recovery). **UDI (U)** corresponds to a clothing ensemble with moderate uniform insulation. **CBRI (C)** is a non-uniform clothing ensemble with regions of high insulation over body areas displaying “colder” temperatures under uniform moderate insulation and regions of low insulation over body areas displaying “warmer” temperatures under uniform moderate insulation. **WBRI (W)** is the exact mirror from CBRI
Despite the absence of CLO effect on overall parameters ($T_{re}$, $T_{sk}$ and $T_b$), the differences in clothing insulation induced different distributions of $T_{sk}$, and this will be discussed in 7.3.4. An overall index to quantify these differences is the within-subject variability in $T_{sk}$ across the whole-body. The overall uniformity was calculated (standard deviations of $T_{sk}$ based on all measured body regions, cf p.241) for each participant and then averaged for the specific clothing condition as reported on Figure 7.6. The main effect of CLO was significant ($p<0.01$) over the protocol with no interaction effect ($p=0.13$), the WBRI condition displaying the largest variability compared to both CBRI and UDI.

Figure 7.6: Evolution of $T_{sk}$ variability across the whole-body for the three clothing conditions (CBRI, UDI, WBRI) at the four protocol stages (PRE, RUN10, RUN40, POST).
* significantly different from CBRI ¤ significantly different from UDI

In summary, the three different clothing conditions induced similar $T_{re}$ and $T_{sk}$ responses but the non-uniformity of $T_{sk}$, sweat accumulated in clothing was larger in WBRI compared to UDI and body sweat loss was larger in WBRI and CBRI compared to UDI.

7.3.3.2. Thermal responses and overall body fat content
A significant negative relationship was found between $T_{sk}$ and %BF over participants on one hand and between $T_{sk}$ and sum of skinfolds on the other hand.
This was consistent for each protocol stage and irrespective of the clothing condition as indicated in Table 7.5. This correlation was also significant when all observations from the three clothing conditions were plotted together.

**Table 7.5.** Table of correlation coefficients (r values) for the relationship between $\overline{T}_{sk}$ and %BF as well as $\overline{T}_{sk}$ and sum of skinfolds (24 body sites) for the three different clothing types CBRI, UDI and WBRI (n=12) and for all observations combined (n=36)

<table>
<thead>
<tr>
<th>%BF</th>
<th>$\overline{T}_{sk}$ at PRE</th>
<th>$\overline{T}_{sk}$ at RUN10</th>
<th>$\overline{T}_{sk}$ at RUN40</th>
<th>$\overline{T}_{sk}$ at POST</th>
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<td>-0.80</td>
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<td>-0.84</td>
<td>-0.73</td>
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<table>
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<th>sum of skinfolds</th>
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<th>$\overline{T}_{sk}$ at RUN10</th>
<th>$\overline{T}_{sk}$ at RUN40</th>
<th>$\overline{T}_{sk}$ at POST</th>
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</thead>
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<td>-0.88</td>
<td>-0.81</td>
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<tr>
<td>ISO</td>
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<td>HOT</td>
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<td>-0.77</td>
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Significant at p<0.05 [ ] p<0.01 [ ] p<0.001 [ ]

Figure 7.7 illustrates the relationship between $\overline{T}_{sk}$ and %BF for the first running stage.

![Figure 7.7](image)

**Figure 7.7:** Relationship between mean skin temperature (°C) and percentage body fat for each clothing type separately (CBRI, UDI, WBRI) after 10 minutes of running at 70% $\dot{V}O_2_{max}$.

*significant at p<0.05 and **significant at p<0.001
Unlike $T_s$, $T_r$ was not correlated with %BF nor was it with metabolic heat production (W or W.m$^{-2}$) at any protocol stage.

7.3.3.3. Metabolic rate
There was no significant effect of CLO on relative or absolute $\dot{VO}_2$ (mL.kg$^{-1}$.min$^{-1}$, p=0.88 and L.min$^{-1}$, p=0.83). Despite being heavier than UDI, CBRI and WBRI did not induce a larger metabolic strain (CBRI vs UDI vs WBRI: 45.1 ± 7.0 mL.kg$^{-1}$.min$^{-1}$ vs 43.2 ± 6.1 mL.kg$^{-1}$.min$^{-1}$ vs 43.4 ± 8.0 mL.kg$^{-1}$.min$^{-1}$, NS).

7.3.3.4. Thermal responses and overall subjective votes
Overall thermal sensation (TS$_{overall}$) was only correlated with $T_s$ at RUN40 for the WBRI condition ($r = 0.73$, p<0.01) and when all observations (CBRI, UDI, WBRI) were combined at RUN40 ($r = 0.42$, p<0.05).

Overall thermal comfort (TC$_{overall}$) was only correlated with $T_s$ for the CBRI condition at RUN10 and RUN40 ($r = -0.64$ and $r = -0.60$, p<0.05), and for the WBRI condition at RUN 40 ($r = -0.60$, p<0.05). Combining data for the three clothing conditions (36 observations), this was also the case at RUN10 and RUN40 ($r = -0.40$ and $r = -0.49$, p<0.05). Comfort was associated with $T_s$ in the 21-23°C range.

The combination of all observations from all stages revealed a significant relationship between TS$_{overall}$ and $T_r$ ($r = 0.55$, p<0.01). TS$_{overall}$ was positively correlated with $T_b$ ($r = 0.51$, p<0.01). TC$_{overall}$ was negatively correlated with $T_s$ specifically during the exercising stages ($r = -0.45$, p<0.01) but not over the whole protocol.

7.3.3.5. Overall subjective votes
The evolution of overall thermal votes over the protocol is presented in Figure 7.8. It indicates that only moderate discomfort was experienced by the participants regardless of CLO and that thermal sensations remained for a large majority on the cold side of the scale, starting from the same baseline for CBRI, UDI and WBRI at PRE (-3.5 i.e cool).

A trend towards significance was highlighted for the overall effect of CLO on TS$_{overall}$ (p=0.051) with warmer sensations overall for WBRI and CBRI compared to UDI (p<0.05) and no difference between WBRI and CBRI. There was no overall
effect of CLO on TC\textsubscript{overall}. At the last stage (POST), participants in CBRI tended to be more comfortable than in UDI (p=0.09).

Figure 7.8: Overall perceptual median responses (thermal sensation, thermal comfort) for the 3 groups: CBRI (■) UDI (+) WBRI (●) at all stages of the running protocol (PRE, RUN10, RUN40, POST).

* significantly different from UDI (p<0.05) # significantly different from UDI at 0.05<p<0.1

Over the whole protocol, the analysis per category of comfort demonstrated that 50% of participants wearing CBRI were in the comfort zone (voting 0) as opposed to 35% for UDI and 40% for WBRI. The largest differences were observed at PRE (comfortable: CBRI: 50%, UDI and WBRI: 25%) and at POST (comfortable: CBRI: 75%, UDI: 50%, WBRI: 58%).

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In summary, the protocol conditions did not strongly discriminate the three clothing ensembles though there was a tendency for clothing CBRI to be better perceived, especially in the post-exercise phase.

7.3.4. Patterns of skin temperature distribution

The following figures (Figure 7.9, 7.10, 7.11, 7.12) provide quantitative data about the topography of skin temperatures for the 3 clothing conditions. The relative maps are obtained by dividing the matrix of the condition absolute map by the condition $T_{sk}$ at that specific stage. This allows for comparison between clothing ensembles in terms of topographical similarities or differences in the $T_{sk}$ patterns. Furthermore, the differences between clothing ensembles from the pre-defined body regions in absolute and relative $T_{sk}$ (relative to each group $T_{sk}$) are presented in Table 7.6 and 7.7.
Figure 7.9: Group-averaged maps of absolute (left panel) and relative (right panel) skin temperature at rest after 5 minutes standing in a 10°C environment (PRE) with uniform distribution of clothing insulation (U) and two opposite distributions of clothing insulation (C and W) after morphing individual images of the 12 participants of each group into a reference body shape. Relative = relative to each condition mean skin temperature (=1).

Figure 7.10: Group-averaged maps of absolute (left panel) and relative (right panel) skin temperature after 10 minutes running at 70% $\dot{V}O_{2\text{max}}$ in a 10°C environment (RUN10) with uniform distribution of clothing insulation (U) and two opposite distributions of clothing insulation (C and W) after morphing individual images of the 12 participants of each group into a reference body shape. Relative = relative to each condition mean skin temperature (=1).
Figure 7.11: Group-averaged maps of absolute (left panel) and relative (right panel) skin temperature after 40 minutes running at 70% \( \dot{V}O_{2,\text{max}} \) in a 10°C environment (RUN40) with uniform distribution of clothing insulation (U) and two opposite distributions of clothing insulation (C and W) after morphing individual images of the 12 participants of each group into a reference body shape. Relative = relative to each condition mean skin temperature (=1).
Figure 7.12: Group-averaged maps of absolute (left panel) and relative (right panel) skin temperature at rest after 10 minutes of post-exercise recovery standing in a 10°C environment (POST) with uniform distribution of clothing insulation (UDI) and two opposite distributions of clothing insulation (CBRI and WBRI) after morphing individual images of the 12 participants of each group into a reference body shape. Relative = relative to each condition mean skin temperature (=1).
Table 7.6: Significance levels of comparUDIns for **ABSOLUTE skin temperature** between clothing types (UDI: U vs CBRI: C vs WBRI: W) at all stages of the protocol (PRE, RUN10, RUN40, POST) for both uncorrected differences and Holm-Bonferroni corrected (at p<0.05).

Significantly different at p<0.05. + indicates a positive and – a negative difference (i.e C warmer than U at region#28 and stage 10)

Grey areas on the manikin correspond to highly insulated regions (C) and thinly insulated regions (H).
Table 7.7: Significance levels of comparisons for RELATIVE skin temperature between clothing types (UDI: U vs CBRI: C vs WBRI: W) at all stages of the protocol (PRE, RUN10, RUN40, POST) for both uncorrected differences and Holm-Bonferroni corrected (at p<0.05).

Significantly different at p<0.05. + indicates a positive and − a negative difference (i.e. W relatively higher than U at region 29 and stage 10).

Grey areas on the manikin correspond to highly insulated regions (C) and thinly insulated regions (H).
From the absolute $T_{sk}$ differences between clothing types (Table 7.6 and 7.8), the largest differences were observed at RUN40 with almost no difference found at PRE. They were more pronounced in the comparison between CBRI and WBRI, as large as 3.9°C in the umbilical region (#13) warmer for CBRI (with high insulation). Overall, the anterior arms, dorsal elbows, upper chest and posterior legs with high insulation (WBRI) were approximately 2°C warmer than in CBRI and UDI. The magnitude of difference even reached 3°C for the back with local $T_{sk}$ differences of up to 3.5°C (scapular and infrascapular regions) warmer for WBRI compared to CBRI and UDI. The anterior torso, anterior legs and posterior upper arms with high insulation (CBRI) were approximately 2.5°C warmer than in WBRI and UDI. Larger local $T_{sk}$ differences were found at the abdomen (4°C) epigastic region (3°C), the thigh and patella (3.5°C).

After exercise, the differences are limited to the warmer back (2°C), upper chest (1.5°C), anterior arms (1°C) and posterior legs (1°C) for WBRI (highly insulated) compared to UDI or CBRI. Based on Figure 7.10 and 7.11, it is worth noting strong similarities in the upper chest and sternal regions between clothing with the largest differences being in the clavicular and the shoulder.

From table 7.8, it was clear that $T_{sk}$ in the small distal or proximal regions (#1,5,7,12) was not strictly influenced by the difference in insulation but more largely by the type of insulation (moderate, high, low) in the main part of the segment (leg, arm, back) next to it.
Table 7.8: Significance levels of comparisons for ABSOLUTE skin temperature in the specific regions of interest between clothing types (UDI: U vs CBRI: C vs WBRI: W) at all stages of the protocol (PRE, RUN10, RUN40, POST) for both uncorrected differences and Holm-Bonferroni corrected (at p<0.05).

Significantly different at p<0.05. Values correspond to the $T_{sk}$ difference between conditions in °C (C-U, W-U, W-C).

On the right, red areas correspond to highly insulated regions (wearing CBRI) and thinly insulated regions (wearing WBRI). Blue areas correspond to highly insulated regions (wearing WBRI) and thinly insulated regions (wearing CBRI). Clothing U has moderate uniform clothing insulation for red and blue areas.

<table>
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<th>SPECIFIC DIFFERENCES</th>
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<td>1.4 1.1</td>
<td>0.9 1.2</td>
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</tr>
</tbody>
</table>

Uncorrected differences Holm-Bonferroni corrected
7.3.5. Local skin temperature and local subjective votes

The 2-way repeated measures ANOVA revealed no significant overall effect of CLO on $T_{sk,local}$ when all stages and regions were taken into account. Local thermal sensation ($T_{local}$) remained within a relatively narrow range on the sensation scale: from -2 (*slightly cool*) to +1 (*towards slightly warm*). The evolution was similar for all body segments with the lowest vote at PRE, a progressive increase towards the end of exercise (RUN40) and either a steady final vote (POST) around *neutral* or a drop below *neutral*.

The overall effect of CLO on $T_{local}$ was significant for 5 out of 11 body segments investigated. Non significant effects were obtained for the posterior aspect of the limbs (posterior legs, posterior arms, dorsal hands) as well as the anterior torso (chest and abdomen). A significant effect of CLO was therefore found for the anterior aspect of the limbs (anterior arms, anterior legs, palmar hands) as well as the posterior torso (upper and lower back) (Figure 7.12).

Most of the significant differences (at specific stages) occurred during exercise and they were more pronounced at RUN40 with up to 2 scale units difference in $T_{local}$ (Figure 7.13). Regions were perceived warmer in the condition with high insulation (WBRI for the back and anterior arms, CBRI for the anterior legs). Although the same gloves were worn for all conditions, palmar hands appeared to be perceived warmer in the WBRI condition compared to CBRI before exercise (PRE).

Our results demonstrate that the influence of CLO on $T_{local}$ was negligible. The only differences reported were limited to two segments: the upper back and anterior arms. Participants wearing WBRI perceived these two segments more comfortable at PRE compared with UDI. Moreover, participants wearing WBRI perceived their upper back less comfortable at RUN40 compared to CBRI. This can be seen in connection with the wetness sensation reported significantly higher for WBRI (wetter) only at the upper back and arms at RUN40 compared to CBRI conditions.

In summary, the influence of additional insulation was mainly observed through warmer $T_{local}$ in WBRI (back and anterior arms) associated with up to 3°C higher $T_{sk,local}$ (back) having a negative influence on $T_{C,local}$ during exercise.
Figure 7.13: Median values for local thermal sensation (TS) and local thermal comfort (TC) at the four different stages (PRE, RUN10, RUN40, POST), for the three different clothing types (CBRI, UDI, WBRI) for five body segments displaying an overall significant effect of CLO (Upper Back, Lower Back, Arms Front, Legs Front, Palmar hands).

* significantly different from UDI (p<0.05) ‡ significantly different from CBRI (p<0.05). Ranges and quartiles are not reported for clarity.
Over the four stages, there was a very limited number of significant correlations between thermal votes (TS\textsubscript{local}, TC\textsubscript{local}, TS\textsubscript{overall}, TC\textsubscript{overall}) and Tsk\textsubscript{local} as presented in table 7.9. For the three separate clothing conditions, only 49 out of 528 potential correlations were significant (9 for UDI, 19 for CBRI, 21 for WBRI). For all clothing conditions combined (n=36), 42 out of 176 potential correlations were significant (7 at PRE, 12 at RUN10, 15 at RUN40, 8 at POST).

Table 7.9 Correlation coefficients table (r values) for the relationship between thermal votes at different body regions and local skin temperatures for the three clothing conditions (UDI, CBRI, WBRI), all conditions combined (ALL) at the four protocol stages (PRE, RUN10, RUN40, POST).

<table>
<thead>
<tr>
<th></th>
<th>OVERALL</th>
<th>CHEST</th>
<th>ABDOMEN</th>
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<th>RIGHT ARM</th>
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**PRE**

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**POST**

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<td>0.00</td>
</tr>
</tbody>
</table>

TS local: Local thermal sensation, TC local: local thermal comfort, TS overall: overall thermal sensation, TC overall: overall thermal comfort. Bold values correspond to the best r values for overall votes. Significant [ ] at p<0.05 [ ] at p<0.01 [ ] at p<0.001

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From Table 7.9, no regional consistency was highlighted except for the dorsal hands (PRE, RUN10, POST) and the chest (at RUN40 and POST). The relationships between \( T_{\text{S,local}} / T_{\text{S,overall}} \) and \( T_{\text{sk,local}} \) were solely positive but this was not the case for \( T_{\text{C,local}} / T_{\text{C,overall}} \). Comfort perception was indeed negatively linked to \( T_{\text{sk,local}} \) especially at the chest, abdomen, anterior and posterior legs and this was more pronounced at RUN40.

The combination of different stages with all clothing conditions (Table 7.10) still demonstrates the poor correlations between perceptual votes (\( T_{\text{S,local}}, T_{\text{S,overall}}, T_{\text{C,local}}, T_{\text{C,overall}} \)) and \( T_{\text{sk,local}} \). On the other hand, some significant correlations with \( T_{\text{S,local}} \) were obtained during exercise for the anterior regions (chest, arms, legs, palmar hands, face; from \( r = 0.42 \) to \( r = 0.48, p<0.01 \)). Face \( T_{\text{sk}} \) was a good predictor of \( T_{\text{S,overall}} \) during the exercising stages (\( r = 0.58, p<0.001 \)).

**Table 7.10** Correlation coefficients table (r values) for the relationship between thermal votes at different body regions and local skin temperatures for the combination of the three clothing conditions and combined data for all stages (144 observations) and exercising stages (72 observations).

<table>
<thead>
<tr>
<th>Body Region</th>
<th>ALL STAGES</th>
<th>EXERCISE STAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( T_{\text{S,local}} )</td>
<td>( T_{\text{C,local}} )</td>
</tr>
<tr>
<td>CHEST</td>
<td>0.04</td>
<td>0.12</td>
</tr>
<tr>
<td>ABDOMEN</td>
<td>-0.15</td>
<td>-0.03</td>
</tr>
<tr>
<td>U.BACK</td>
<td>0.00</td>
<td>-0.15</td>
</tr>
<tr>
<td>L.BACK</td>
<td>-0.06</td>
<td>0.03</td>
</tr>
<tr>
<td>ARMS ant.</td>
<td>0.11</td>
<td>0.03</td>
</tr>
<tr>
<td>ARMS post.</td>
<td>-0.04</td>
<td>0.06</td>
</tr>
<tr>
<td>LEGS ant.</td>
<td>-0.18</td>
<td>-0.06</td>
</tr>
<tr>
<td>LEGS post.</td>
<td>-0.29</td>
<td>-0.35</td>
</tr>
<tr>
<td>HANDS back</td>
<td>0.34</td>
<td>0.41</td>
</tr>
<tr>
<td>HANDS palm</td>
<td>0.38</td>
<td>0.23</td>
</tr>
<tr>
<td>FACE</td>
<td>0.30</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Using a within-subjects approach (between-regions), the distribution of local thermal votes (\( T_{\text{S,local}}, T_{\text{C,local}} \)) was analysed in relation to the distribution of \( T_{\text{sk,local}} \) for the 11 corresponding large regions investigated. Significant correlations were found using average values for \( T_{\text{S,local}} \) and \( T_{\text{sk,local}} \) for the WBRI condition at RUN10 and RUN40 (\( r = 0.63, p<0.05 \) and \( r = 0.65, p<0.05 \)). This was confirmed when distributions for each individual wearing WBRI were analysed (7 out of 12 individuals displaying significant correlations). The correlations were non significant for the CBRI and UDI conditions at all stages. No relationships between the distribution of \( T_{\text{C,local}} \) and \( T_{\text{sk,local}} \) were found for any of the clothing condition.
In summary, there was no evidence that thermal votes were correlated with $T_{sk,local}$ over participants in the different regions investigated. Similar to Chapter 6, face $T_{sk}$ was a good predictor of $TS_{overall}$. Lastly, the distribution of $T_{sk,local}$ across the body explained the distribution of $TS_{local}$ only in WBRI, with large $T_{sk}$ non-uniformity.

### 7.3.6. Local skin temperature and local skinfold thickness

The measurements of 24 skinfold thickness sites were analysed in association with $T_{sk}$ of the same regions from the whole-body $T_{sk}$ segmentation (17 corresponding regions in total) similar to Chapter 3.

#### Table 7.11 Correlation coefficients table ($r$ values) for the relationship between local skin temperatures ($°C$) and local skinfold thickness (mm) at 17 different body regions for the three groups (UDI, CBRI, WBRI, n=12) and all conditions combined (ALL, n=36).

<table>
<thead>
<tr>
<th>Region</th>
<th>PRE</th>
<th>RUN10</th>
<th>RUN40</th>
<th>POST</th>
<th>ALL</th>
<th>UDI</th>
<th>CBRI</th>
<th>WBRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forearm</td>
<td>-0.17</td>
<td>-0.61</td>
<td>-0.46</td>
<td>-0.12</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.52</td>
</tr>
<tr>
<td>Ant. Biceps</td>
<td>-0.28</td>
<td>-0.61</td>
<td>-0.46</td>
<td>-0.12</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.52</td>
</tr>
<tr>
<td>Shoulder</td>
<td>-0.27</td>
<td>-0.61</td>
<td>-0.46</td>
<td>-0.12</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.52</td>
</tr>
<tr>
<td>Pectoral</td>
<td>-0.27</td>
<td>-0.61</td>
<td>-0.46</td>
<td>-0.12</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.52</td>
</tr>
<tr>
<td>Clavicular</td>
<td>-0.27</td>
<td>-0.61</td>
<td>-0.46</td>
<td>-0.12</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.52</td>
</tr>
<tr>
<td>External Oblique</td>
<td>-0.27</td>
<td>-0.61</td>
<td>-0.46</td>
<td>-0.12</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.52</td>
</tr>
<tr>
<td>Upper Abdominal</td>
<td>-0.27</td>
<td>-0.61</td>
<td>-0.46</td>
<td>-0.12</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.52</td>
</tr>
<tr>
<td>Suprailliac</td>
<td>-0.27</td>
<td>-0.61</td>
<td>-0.46</td>
<td>-0.12</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.52</td>
</tr>
<tr>
<td>Abdominal</td>
<td>-0.27</td>
<td>-0.61</td>
<td>-0.46</td>
<td>-0.12</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.52</td>
</tr>
<tr>
<td>Scapular</td>
<td>-0.27</td>
<td>-0.61</td>
<td>-0.46</td>
<td>-0.12</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.52</td>
</tr>
<tr>
<td>Triceps</td>
<td>-0.27</td>
<td>-0.61</td>
<td>-0.46</td>
<td>-0.12</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.52</td>
</tr>
<tr>
<td>Forearm Post.</td>
<td>-0.27</td>
<td>-0.61</td>
<td>-0.46</td>
<td>-0.12</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.55</td>
<td>-0.52</td>
</tr>
</tbody>
</table>

Table 7.11 indicates that a consistent regional determinism existed for most of the body sites (biceps, shoulder, pectoral, external oblique, upper abdominal, suprailliac, abdominal, triceps, thigh, calf) regardless of the different clothing conditions. The relationships were less pronounced in the uniform clothing condition (UDI) compared to the non-uniform conditions (CBRI and WBRI).

Using a within-subjects approach (between-regions), the distribution of $T_{sk,local}$ was analysed in relation to the distribution of skinfold thickness for the 17 corresponding regions investigated.

When all the 17 sites were taken into account, no significant correlations were found for any clothing condition at any protocol stage. However, a significant correlation was highlighted for WBRI at RUN40 when sites from the anterior torso (9 in total) were analysed ($r = -0.70$, p<0.05). This was confirmed on an individual basis with
the majority of participants displaying the significant relationship between the
distribution of T
 subscripts sk and the distribution of skinfold thickness across the anterior torso.
The correlations using the anterior torso or posterior torso separately were non
significant for the CBRI and UDI conditions at all stages.
In summary, T
 subscripts sk,local was correlated with local skinfold thickness in this protocol with
clothed participants irrespective of the clothing condition and for most body sites.
The distribution of skinfold thickness explained the variations of T
 subscripts sk,local across the
anterior torso in clothing WBRI only.

7.4. Discussion

The aim of the present study was to manipulate local T
 subscripts sk by means of different
clothing ensembles having uniform or non-uniform distribution of clothing insulation
over the whole-body. The distribution was defined from previous body maps
obtained whilst running and this activity was once again tested to investigate the
influence of the clothing ensembles on thermal sensation and comfort. The
philosophy behind the manipulation was to either protect hot regions, likely to
dampen heat dissipation, or protect cold regions, leading to less extreme T
 subscripts sk,local potentially favourable for thermal comfort. Based on this principle the two clothing
ensembles were supposed to create two specific patterns of T
 subscripts sk:
  - an accentuated pattern of T
 subscripts sk with increased contrasts between regions by
    adding insulation to the normally “warm” regions and having less insulation
    over the normally “cold” regions (clothing WBRI).
  - a minimized pattern of T
 subscripts sk with a reduction of the variability between regions
    by adding insulation to the normally “cold” regions and having less insulation
    over the normally “warm” regions (clothing CBRI).
The new patterns were also compared to a reference pattern (UDI) obtained in the
exact same conditions with the same participants. The intervention was directed
towards creating distinct patterns but keeping the overall T
 mean similar. To our
knowledge, this type of approach has never been used in the literature, with
modifications of intra-segmental insulation. Clothing with different configurations
have mainly been studied with differences between peripheral and central regions
(Nielsen and Nielsen, 1984; Gwosdow and Berglund, 1987; Lee and Tokura 1993;
Kim et al., 2008) or full vs partial coverage (Vokac et al., 1971; Hanada et al., 1982,
Jeong et al., 1988, 1989, 1990; Sari and Candas, 1992; Rissanen et al., 1996; Lee and Tokura 1998). Our investigation was the first to modify insulation within body segments on a sport garment with a single layer (top and tights). As coverage was considered “full” for all our conditions, the discussion will be mainly related to the non-uniformity of clothing insulation.

The main findings were that the manipulation of $T_{sk}$ was successful leading to the same $\bar{T}_{sk}$ throughout the running protocol as well as the same $T_{re}$, but producing three different patterns of $T_{sk}$ as observed by the relative body maps of $T_{sk}$ distribution. Body sweat loss and sweat accumulated in the clothing ensemble were the lowest in UDI. The different insulation distributions induced specific local perceptions with the expectedly warmer sensations for the highly insulated body regions causing either comfort during the resting phases or warm discomfort during the exercising phases. It was worth noting that the effect of clothing type was significant for $TS_{local}$ and $TS_{overall}$ but not for $TC_{local}$ and $TC_{overall}$. The distribution of $TS_{local}$ was found to be significantly correlated with $T_{sk,local}$ only in WBRI during exercise, where the non-uniformity of $T_{sk,local}$ was large.

7.4.1. The influence of clothing insulation distribution

7.4.1.1. Overall thermal and cardiovascular responses

The effect of CLO and the interaction TIME*CLO were not significant on $T_{re}$. This result is consistent with other studies using non-uniform insulation at rest (Vokac et al., 1971; Gwosdow and Berglund, 1987) and during exercise (Nielsen and Nielsen, 1984).

The study by Nielsen and Nielsen (1984) however found a larger $T_{re}$ decrease during post-exercise recovery in the high insulated LIMBS (L) vs the high insulated TORSO conditions (T).
Heat production was similar for L and T but the larger heat loss from the torso in the L condition was deemed responsible for this discrepancy. In our conditions, heat production was similar between clothing ensembles and the avenues for heat loss were locally specific for each body region. Clothing WBRI was targeting the regions with usually larger temperature gradient from the body to the environment. Because $T_{re}$ was not significantly influenced, it can be suggested that the WBRI condition did not cause a relevant enough reduction of dry heat loss from these regions neither at rest nor during exercise to affect $T_{re}$. This may have been offset by a larger heat loss (dry and wet) from the thinly insulated regions. Moreover, the distribution of insulation was well balanced within the upper and lower body for CBRI and WBRI unlike T and L in Nielsen and Nielsen (1984). The larger sweat accumulation in the running top in WBRI could also have caused reduction in insulation and larger heat loss even from the highly insulated regions (such as the back).

Kim et al. (2008) showed an effect of clothing distribution on $T_{re}$ of 6 adolescents both during exercise and post-exercise recovery comparing three ensembles A (low insulation over the upper body, high insulation over the lower body) B (the opposite to A) and C (moderate insulation all over). Clothing B had the lowest rise in $T_{re}$ during exercise as well as the lowest drop during the 2h recovery, potentially due to a more efficient counter-current heat exchange, with a deeper venous return in the thinly insulated lower body (Lee and Tokura, 1998). Although the clothing configuration principle was similar to ours (high, low and moderate insulation), the protocol and clothing ensembles varied drastically from our study with differences in total clothing mass (~1800g for A,B,C compared to ~800g for CBRI, UDI and
WBRI), total duration (150min vs 60min), $T_a$ (10°C vs 5°C) air velocity (0.1 vs 2.8 m.s$^{-1}$) and heat production (200W.m$^{-2}$ vs 600W.m$^{-2}$).

In the present study, the effect of CLO and the interaction TIME*CLO were not significant on $\bar{T}_{sk}$ and $\bar{T}_b$. In Nielsen and Nielsen (1984), $\bar{T}_{sk}$ and $\bar{T}_b$ were significantly higher in L than T during exercise (1h) and rest (1h) by 0.8°C and 0.2°C respectively. In Kim et al. (2008), the two ensemble with non-uniform distribution (A: higher lower B: high upper) had similar $\bar{T}_{sk}$ both during exercise (30min) and recovery (2h). Lastly, participants wearing asymmetric clothing for 3h at 18°C had similar $\bar{T}_{sk}$ as with symmetric clothing (Gwosdow and Berglund, 1987). Conclusions are relatively difficult as total insulation, surface covered by high insulation, environmental stress and type of exposure vary widely between studies. It is worth noting that $\bar{T}_{sk}$ was computed from contact sensor measurements from 9 to 13 sites in the other studies with the same coefficients as used in nude or evenly clothed experiments. The advantage of our mapping technique was the production of a true $\bar{T}_{sk}$. The similarity in $\bar{T}_{sk}$ highlighted our successful manipulation though this was relatively hypothetical at the start. Modifications in insulation implied changes in other clothing thermal properties with slightly different fit due to the stretch of the prototypes induced by juxtaposing fabrics with different properties.

Unlike Chapter 3 (unclothed males), $\bar{T}_{sk}$ was negatively correlated with %BF on one hand and sum of skinfolds on the other hand. This was true at all stages, for clothing conditions separately (CBRI, UDI, WBRI) and when all conditions were combined (Table 7.5 and Figure 7.7). The group of clothed males in the present study had a larger range of body fat content compared to the semi-nude runners from Chapter 3 (overall range: 13% vs 7%). The relationships between $\bar{T}_{sk}$ and %BF has been reported during resting cold exposure as found in Chapter 4 (LeBlanc, 1954; Baker and Daniels, 1956; Oksa et al., 1993) but never during clothed exercise except in Chapter 6. This is a relatively original finding and we may assume that this relationship would be highlighted in future experiments providing that the range of body fat content in the population is sufficiently large (%BF range >10%).
Metabolic heat production (M) was not influenced by CLO and this was in line with all the other studies involving different clothing distribution (Vokac et al., 1971, Nielsen and Nielsen 1984; Gwosdow and Berglund 1987; Lee and Tokura 1993, Kim et al.; 2008). In our case, the difference of only 290g (WBRI – UDI) was negligible. In the field of protective clothing, Dorman and Havenith (2008) demonstrated that increase in metabolic rate became significant (>5%) with additional weight of approximately 4kg. Moreover, Brownlie et al. (1987) stated that the measurement of exercise oxygen uptake is probably sufficient only to discriminate between relative work rates but does not have sufficient resolution to discriminate between different sport garments under similar conditions of work rate and ambient environment.

Similar to metabolic heat production, HR remained identical between clothing conditions (150bpm during exercise) and so was RPE (12- between light and somewhat hard). No indications of HR responses or RPE were reported in other studies about different clothing configuration. It can be assumed that clothing with non-uniform distribution would not have a significant impact on HR and RPE.

Sweating was affected by CLO with the largest sweat loss and sweat accumulation for participants wearing WBRI with highly insulated regions over the naturally “warm” regions. These warm regions also correspond to regions of high sweat production in the back whilst running at 70% $\dot{V}O_{2,max}$ (Smith and Havenith, 2012) where additional insulation has pushed local $T_{sk}$ (>2°C over the back in WBRI vs CBRI and UDI) and potentially local sweat rates. This barrier of relatively high vapour resistance (coinciding with the increased dry heat resistance) may have favoured sweat production and then accumulation (>30g more in the running top for WBRI vs CBRI and UDI), forcing dry and evaporative heat loss to be maximised in another region which was most likely the anterior legs. Kim et al. (2008) reported their uniform clothing (C) to elicit the largest forearm sweat rates (+60% compared to clothing A and B) and total amount of sweating (+80%). This was discussed in association with the higher $\overline{T}_{sk}$ and $T_{re}$ in C (+2°C and +0.2°C vs A and B) throughout the majority of the protocol (Kim et al., 2008). Despite the low exercise intensity (150 W.m$^{-2}$), sweat loss was unfortunately not reported in Nielsen and Nielsen (1984).
Further investigation using our clothing ensembles should also focus on regional sweat rates as the regional placing of insulation may largely affect local sweat production.

- Despite differences in overall weight and insulation distribution, the three clothing ensembles induced similar responses in $T_{re}$, $\overline{T}_{sk}$, $\overline{T}_b$, M, HR and RPE. It can be concluded that the overall heat loss was similar despite regional specificities. Targeting warm regions with high insulation induced more overall sweating.

7.4.1.2. Regional skin temperature responses

Similar to the previous experiment, the present investigation was the first to use a whole-body mapping approach for exercising males wearing clothing with different insulation distribution. Livingstone et al. (1988) measured torso $T_{sk}$ distribution using infrared thermography on a group of five males at rest after 60 min of 5°C exposure in a single, double or triple layer of clothing. This experiment was the closest to our protocol but not performed during exercise and limited to the analysis of the torso.

The non-uniformity of $T_{sk}$ over the body confirmed the successful manipulation of whole-body $T_{sk}$ with clothing CBRI having the lowest $T_{sk}$ variability across the body (1.8°C) and WBRI the largest (2.4°C), matching our hypothesis. For people in comfort at rest, Olesen and Fanger (1973) found a $T_{sk}$ uniformity of 1.2°C. Our Participants experienced comfort (POST) and moderate discomfort (RUN40) with much larger $T_{sk}$ uniformity which suggest that people tolerate a much wider $T_{sk}$ variations across the body during exercise and post-exercise. This goes in line with the preference for cooler ambient environments during exercise (Fanger, 1970). In Nielsen and Nielsen (1984), values of $T_{sk}$ uniformity were computed and found to be larger in T (high insulation in torso) compared to L (high in limbs), both during exercise and recovery (3.9°C vs 1.6°C and 3.7°C vs 1.5°C).

Some regional specificities in $T_{sk}$ were observed through the absolute body maps (Figure 7.9-7.12) and quantified for pre-defined regions (Table 7.6) or according to the specific regional design (Table 7.8). In general, the small regions with low insulation are largely influenced by the juxtaposed highly insulated region. Overall,
the $T_{sk}$ differences between differently insulated regions were most pronounced at the end of exercise (RUN40) and this was also the case in Nielsen and Nielsen (1984) but not in Kim et al. (2008) where the recovery period was prolonged to 2 hours in a 10°C environment.

Our results showed that highly insulated regions were 2 to 2.5°C warmer than thinly or moderately insulated regions. Locally, the scapular and infrascapular were 3.5°C warmer in WBRI vs CBRI and the thigh/patella and abdomen 3.5-4°C warmer in CBRI vs WBRI.

These regions were highly influenced by clothing insulation and this was expected as they are among the warmest and coldest regions of the natural pattern (see UDI). In Nielsen and Nielsen (1984), $T_{sk}$ differences of corresponding regions (covered with high or low insulation) reached an average of 3°C over the trunk (max +4.4°C for scapula) and 4°C in the limbs (max 6.4°C for hands). This was slightly more important for the lower body in Kim et al. (2008) with 5-6°C $T_{sk}$ difference, due to a much larger insulation difference.

It can be concluded that our manipulation did not elicit the large contrasts found in the literature but considering the low insulation of the sports garments tested, it was judged to be at the edge of realistic adjustments potentially made for sport ensemble, especially for one-layer garments.

A limitation to our procedure lied in the garment fit at the collar which slightly influenced regional $T_{sk}$ for CBRI and WBRI as can be seen in Figure 7.10. The cut of the collar was slightly more open in the prototypes WBRI and CBRI compared to UDI. This may have favoured air flow (inlet) through the clothing especially during the exercising stages. Moreover, overall stretch was not optimal in WBRI and CBRI compared to UDI.

- The impact of high insulation was on average a 2 to 2.5°C increase compared to thinly insulated corresponding region irrespective of placing this insulation on naturally “warm” or “cold” regions. This manipulation of intra-segmental insulation successfully reduced the heterogeneity of $T_{sk}$ in clothing CBRI compared to WBRI and UDI. Unlike other studies, regional $T_{sk}$ variations were sufficiently well balanced over the body to create similar $\bar{T}_{sk}$. 


7.4.1.3. Patterns of absolute and relative skin temperature

A topographical analysis using the $T_{sk}$ body maps was important, considering $\bar{T}_{sk}$ was similar between clothing conditions, in order to highlight similarities and differences in the whole-body $T_{sk}$ patterns.

Regardless of the clothing conditions, the lower body was colder than the upper body. The cold regions were observed over the abdomen, pectorals, thighs, patella, upper hamstrings, triceps and cheeks. On the other hand, the warm regions corresponded to the upper chest, spine, inner thighs, calves, lateral torso and the natural body creases (elbow crease, popliteal fossa, orbits). Similar to Chapter 3, a Y-shape of colder $T_{sk}$ was easily distinguishable over the anterior-torso and a Y-shape of warmer $T_{sk}$ over the posterior torso. These features are well in line with various reports using infra-red thermography during exercise, specifically running in semi-nude condition (Veghte, 1965; Cena and Clark, 1976; Clark et al., 1977; Vegthe et al., 1979). It is important to highlight that the $T_{sk}$ patterns and the locally cold and warm regions were relatively consistent throughout the protocol though being more accentuated during the exercising stages compared to the resting stages. Spatial delimitations of each isotherm region were definitely more marked with strong $T_{sk}$ differences over limited regions (e.g. pectorals vs upper chest) during exercise.

Due to our manipulation, WBRI was reinforcing the natural Tsk pattern and CBRI attenuating this pattern. The features observed in CBRI therefore demonstrated the important consistency of the normal pattern. Some slight topographical differences were yet observed. The Y-shape over the anterior torso was not entirely discernible in CBRI because the extra insulation had a strong impact on the epigastric regions being warmer than average (above umbilical). The extra insulation also largely influenced the thighs (colder in natural pattern). The thin insulation had a large impact on the collar and shoulder regions as well as in the lateral parts of the back (warmer in natural pattern). It is worth noting that these main differences almost vanished during the post-exercise recovery, with the reappearance of the Y-shape pattern of cold temperatures over the anterior torso (high insulation), or the rewarming of the upper chest and lateral back torso (thin insulation). It could be hypothesized that excessive heat stored during the exercise was favourably lost from the thinly insulated regions of the upper body (in a situation with limited convective
heat loss), therefore reinforcing the natural $T_{sk}$ pattern. Unfortunately, our $T_{sk}$ body maps could not be compared with existing literature on clothing distribution.

The relationships between local $T_{sk}$ and local skinfold thickness revealed significant negative correlation for most body regions (10 out 17) regardless of clothing conditions. This finding echoes well the results from Chapter 4 during resting cold air exposure in a semi-nude condition (see 4.2.9). There was no relationship at body sites with low skinfold thickness (e.g. forearm anterior, patella) but unlike Chapter 4 also at sites with the largest skinfold thickness (hip and infrascapular) potentially due to differences in garment fit at the back region.

The distribution of $T_{sk}$ across the body was not correlated with the distribution of skinfold thickness as demonstrated by our within-subjects approach. However for WBRI at RUN40, this relationship was true for a selection of the 9 anterior torso body sites. This result suggests that the thin insulation over the torso WBRI reinforced the contrasts between skinfold sites, more importantly than moderate uniform insulation (UDI) and towards the same extent as found in Chapter 3 (semi-nude runners). The relationship was significant only at RUN40 (here and Chapter 3) where $T_{sk}$ non-uniformity is the largest. It can be hypothesized that this Y-shape region over the anterior torso, extensively cooled in WBRI, corresponds to the shape of the main fat deposits (Frim et al., 1990) in association with insulation provided by unperfused pectoral and abdominal muscles (Veicesteinas, 1982). If true, this would suggest that external cooling (such as convective cooling) and/or forced convection (running exercise) is required to accentuate differences between regions of varying skinfold thickness.

Similar to our finding, Clark et al. (1977) indicated that the relationship with skinfold thickness was not existent over the back. This was true in the present study but also in Chapter 4 (rest and cycling at 10°C) even with males with large %BF having a more heterogeneous $T_{sk}$ pattern over the back. Our hypothesis is that the spine is well supplied with cutaneous circulation in combination with thin skin and fat insulation, and there is a rich network of vessels between the scapulae. This superficial circulatory specificity could be reminiscent from the position of highly perfused brown fat in early life (Figure 7.14). It is also relatively striking to compare the position of brown fat deposits in infants and the shape of the warm $T_{sk}$ isotherm in adults at rest or during exercise (Figure 7.9-7.12).
In newborns, brown fat is supposed to have insulatory benefits, especially over the heart and the main arteries (carotid, subclavian and thoracic) as well as heat generation capabilities. Brown fat has been found in adults, more specifically in lean persons exposed to cold (van Marken Lichtenbelt et al., 2009) and it is located on the upper chest and neck (Cypess et al., 2009). However, its importance in heat production remains to be fully investigated. A recent study by Symonds et al. (2012) demonstrated an increase in $T_{sk}$ in the supra-clavicular region which is a common WBRI spot in our conditions and a main site of brown fat deposit (Cypess et al., 2009). The quick $T_{sk}$ increase compared to the surrounding tissues was assumed to be related to brown fat thermogenesis and not local increase of cutaneous blood flow. The $T_{sk}$ increase was confined to this supra-clavicular region and inversely correlated with age but relatively small (0.6°C for the 3-8 year old group vs 0.2°C for the 35-58 year old group). Whether brown fat thermogenesis may explain some hot spots during exercise in the cold remains to be explored for the understanding of the $T_{sk}$ patterns. Perforator vessels have been described to play a role in heat dissipation especially at the cessation of exercise (Hunold et al., 1992; Binzoni, 2004; Merla et al., 2010) and it can be hypothesized that the superficial vessels in the upper chest and upper back (reminiscent of early life or not) may be a dense network of perforators or specialised vessels for heat loss (Hoogland et al., 2012) located very close to the surface.

- The different clothing ensembles induced different patterns of $T_{sk}$ distribution with differences being more pronounced during exercise and over the anterior part of the body. Despite a distribution of insulation in CBRI opposite to a normal pattern, some consistent features were still observed such as the
warmer upper chest and creases, the Y-shape over the posterior torso and the colder lower body compared to the upper body. Local skinfold thickness explained the inter-individual variability in local $T_{sk}$ regardless of the clothing ensemble but it only explained the intra-individual distribution of $T_{sk}$ in WBRI, where differences between regions were accentuated. The blood supply to existing or past brown fat deposits may be an important contributor to the $T_{sk}$ patterns in the upper body.

7.4.1.4. Overall and regional perceptual responses

Based on the different subjective votes, the influence of the clothing conditions was relatively limited despite differences in the $T_{sk}$ patterns. The two non-uniform clothing distributions (WBRI and CBRI) were neither detrimental nor beneficial for $TC_{overall}$. It is important to mention that only moderate discomfort was experienced in the protocol. There were still more positive comfort ratings for the CBRI condition overall and a trend toward significance at POST with participants being more comfortable in CBRI than UDI. This better comfort rating was associated with the significantly warmer $TS_{overall}$ (2 scale units) for CBRI compared to UDI at POST. This observation goes in favour of the hypothesis that targeting the cold regions with extra insulation would be beneficial for thermal comfort (Havenith et al., 2008b). Futures studies should look at low metabolic rates (rest or walking) or more extreme environmental conditions to be in a situation of negative heat balance, especially for the test of the WBRI ensemble which might better prevent heat dissipation.

The overall perceptual differences were minimal and it can be hypothesized that the similarities in $T_{sk}$ and $T_{re}$ responses were the most important irrespective of the differences in the $T_{sk}$ patterns. These findings are in agreement with the results by Nielsen and Nielsen (1984) and Vokac et al. (1971). They suggested a spatial summation in a quantitative manner of the afferent thermal information, being either peripheral or central. We observed a significant positive correlation between $TS_{overall}$ and $T_{b}$ ($r = 0.51$) only during the exercising phases whereas the two studies reported strong relationships for the duration of their protocol ($r = 0.71$ and $r = 0.97$). Over the whole protocol, the best correlation was between $TS_{overall}$ and $T_{re}$ ($r = 0.55$). The studies presented had no expression of pleasantness or comfort. It was interesting to observe a negative relationship between $TC_{overall}$ and $T_{sk}$ ($r = -0.45$)
during exercise with comfortable $\overline{T}_{sk}$ in the 21-23°C range. Fanger (1970) stated that the preferred $\overline{T}_{sk}$ with increasing metabolic rate would be lower. In our situation, $\overline{T}_{sk}$ was indeed much lower than the preferred 33°C for thermal neutrality at rest but this negative relationship somehow demonstrated a potential alliesthesial drive (Cabanac, 1971). During the exercise-induced rise in $T_{core}$ (central signal), the participants preferred a colder $\overline{T}_{sk}$ (peripheral signal).

This observation had some regional significance because most of the relationships between $TC_{local}$ and $T_{sk,local}$ were negative (Table 7.9). A practical extrapolation of this finding implies that manipulating clothing INSULATION was not the key factor during exercise at moderate to high intensity, as shown by the local perceptual responses at the anterior arms and the upper back during exercise. In WBRI (i.e. covered with high insulation), they were both perceived warmer and wetter during exercise than in other clothing conditions and this had a negative effect on comfort (Figure 7.13). On the other hand, we found a beneficial effect of high insulation before exercise in these same regions and there was no detrimental effect of thin insulation in any of the body regions.

Unlike Vokac et al. (1971) and Gwosdow and Berglund (1987), we found a limited number of significant correlations between $TS_{local}$ and $T_{sk,local}$ (Table 7.9). In these experiments, different clothing ensembles were tested in two or three different ambient temperatures, thus favouring the link between $TS_{local}$ and $T_{sk,local}$. Similar to our study, Nielsen and Nielsen (1984) only tested in one ambient condition and they also found no relationships between $TS_{local}$ and $T_{sk,local}$. $TS_{local}$ changed in parallel with $TS_{overall}$ which agreed well with our results. Some exceptions occurred in our study for the dorsal hands at all stages (Table 7.9) and mainly for the chest, anterior arms and legs at RUN40.

The analysis of significant differences in $TS_{local}$ between clothing conditions revealed that a minimum of 2°C was necessary to cause a significant change of 2 scale units on the sensation scale. Paradoxically, the anterior arms were perceived significantly warmer for WBRI at PRE with only 0.5°C $T_{sk}$ difference compared to CBRI and UDI. On the other hand, $TS_{local}$ of the back was similar for all conditions whereas it was 2°C significantly warmer in WBRI than CBRI at RUN40.

It is important to keep in mind that modifications of the insulation were made across the body and that strict comparisons of regions are not possible. Hands are a good
illustration because they were perceived colder in CBRI compared to WBRI whereas the gloves’ insulation was locally similar. There was therefore a local, segmental and potentially central interaction with the insulation of more proximal regions. It could be hypothesized that hemodynamic changes may occur with variations of insulation in the limbs.

Lastly, the distribution of local $T_{sk}$ contributed to the variations of $T_{S_{local}}$ across the body (within-subjects) for the WBRI condition at RUN10 and RUN40, in a situation with accentuated normal pattern compared to CBRI and UDI. This relationship also interestingly occurred in Chapter 3 where $T_{sk}$ non-uniformity was even more pronounced. This therefore suggests that this specificity only occurred with large environmental cooling (nude or thinly insulated naturally cold regions).

- Targeting the naturally cold regions with insulation may have a comfort advantage during rest and exercise in the cold. However, the present results also highlight the issues of excessive insulation on wetness and warm sensation during exercise. Unlike other studies, no clear determinism was found between local perceptions and local $T_{sk}$, a 2°C $T_{sk}$ difference was not consistently sufficient to induce a perceptual difference. Participants were able to perceive $T_{sk}$ differences between regions only when these differences were strongly accentuated (with WBRI and during exercise).

### 7.4.2. The comparison of clothed and nude mappings

In addition to the main focus into clothing distribution, the present experiment provided data using the same methodology used for nude $T_{sk}$ body mapping (Chapter 3). A statistical comparison was deemed inappropriate because of some differences in group characteristics and one external determinant ($T_a$ was 10°C in Chapter 3). This would still offer some qualitative and quantitative insights into the influence of CLOTHING per se on thermal parameters. Moreover, the definition of the prototypes’ design (2.3.1) was based on trials where air velocity was slightly different than the final study protocol (2.3.2). Some insights into the role of AIR VELOCITY will also be briefly discussed.

#### 7.4.2.1. Description of clothed and nude responses

The following section provides the most important figures focused on $T_{sk}$ responses: $\bar{T}_{sk}$ and $T_{sk}$ mapping.
Figure 7.15: Evolution of mean skin temperature ($T_{sk}$) for three groups in three different conditions: nude at 10°C (NUDE 10°C), clothed with uniform insulation at 5°C including 2.8 m.s-1 (CLOTHED 5°C), and clothed with uniform insulation at 5°C with additional 2 m.s-1 air velocity (CLOTHED 5°C wind). They all performed the same running scenario: 5’ rest (PRE) 10 minutes of running at 70% $VO_{2\text{max}}$ (RUN10), 30 minutes of running at 70% $VO_{2\text{max}}$ (RUN40) and 10’ of post-exercise recovery (POST).

In Figure 7.16 7.17, body maps at PRE are not presented because they are almost identical between conditions. The two major differences were:

- colder lower body in the clothed conditions
- three localised cold spots at the abdominal and pectoral regions for the clothed condition with additional 2 m.s$^{-1}$

Body maps at RUN10 are not presented because they are similar to the ones at RUN40, the the $T_{sk}$ contrasts between regions being more accentuated at RUN40.

7.4.2.2. The influence of clothing

The main specific features of the nude $T_{sk}$ patterns can be observed on the clothed patterns too. This included the Y-shape of colder $T_{sk}$ over the anterior torso, the colder thighs compared to the calves, the colder upper hamstrings and triceps as well as the Y-shape of warmer $T_{sk}$ over the posterior torso, the warmer upper chest and creases (elbow crease, popliteal fossa and orbits). On the other hand, two major differences were observed between nude and clothed mapping:

- warmer $T_{sk}$ at the upper chest and forearms for the clothed condition
- warmer $T_{sk}$ at the calves and posterior legs for the nude condition.
Although hypothetical, this could represent two different ways to maximise heat loss. In the nude situation, heat was directly conducted from working muscles and easily dissipated in the moving lower limbs. In the clothed condition, heat could be conveyed all the way to the heart and easily dissipated when quitting it from the aortic arch.

In the literature, Livingstone et al. (1988) reported that torso $T_{sk}$ distribution remained constant while the subjects cooled without clothing or immediately after wearing single, double or triple layers of uniform insulation. In our protocol, some consistent features were also found and over the whole-body, not only the torso, there are slight differences in the $T_{sk}$ distribution. A strict comparison of clothed and nude participants could confirm these differences.

Regarding $\bar{T}_{sk}$, the major difference were highlighted only at PRE due to the environmental conditions (1.5°C higher in nude) and in the $\bar{T}_{ad}$ dynamics with more intense cooling and rewarming without clothing.

- Despite similar $\bar{T}_{ad}$ for the nude and clothed datasets, $T_{sk}$ distribution was slightly different showing specific hot spots at the upper chest with clothing and in the calves, posterior legs without clothing. The topography of the main regions was identical with and without clothing.
Figure 7.16: Group-averaged maps of absolute (left panel) and relative (right panel) skin temperature after 40 minutes running at 70% $\dot{V}O_{2\text{max}}$ in a nude condition at 10°C, a uniformly clothed condition at 5°C with 2.8 m.s$^{-1}$, a uniformly clothed condition at 5°C with 5 m.s$^{-1}$ after morphing individual images of the 12 participants of each group into a reference body shape. N.B: the three conditions were obtained from three separate groups Relative = relative to each condition mean skin temperature (=1).
Figure 7.17: Group-averaged maps of absolute (left panel) and relative (right panel) skin temperature at rest after 10 minutes of post-exercise recovery standing in a nude condition at 10°C, a uniformly clothed condition at 5°C with 2.8 m.s⁻¹, a uniformly clothed condition at 5°C with 5 m.s⁻¹ after morphing individual images of the 12 participants of each group into a reference body shape. N.B: the three conditions were obtained from three separate groups. Relative = relative to each condition mean skin temperature (=1).
7.4.2.3. The influence of air velocity

The comparison of the clothed conditions with two types of wind exposure highlighted the contribution of frontal AIR VELOCITY to the $T_{sk}$ patterns. The addition of 2 m.s$^{-1}$ flow induced a larger Y-shape of colder $T_{sk}$ and a strong impact on the exposed body regions such as the neck and cheeks (lower $T_{sk}$). Figure 7.17 shows that $T_{sk}$ was similar between conditions. This implies that warmer areas were present to compensate for the large impact on the torso. This redistribution was in favour of posterior legs, the forearms and the upper thighs displaying warmer $T_{sk}$ compared to the other clothed condition.

Clark et al. (1977) have reported little change in the $T_{sk}$ distribution once air flow (4.5 m.s$^{-1}$) was turned on with an immediate $T_{sk}$ fall of 4°C, but clear consistencies with the cold abdomen and warm active muscles.

The general effect of AIR VELOCITY can also be discussed in the light of studies using contact measurements during exercise in the cold. Mäkinen et al. (2001) found that a change from 1 to 5 m.s$^{-1}$ strongly affected the exposed body parts (head, hands) and the chest with a larger heat flux measured on men wearing military clothing. The surface and clothing layers were largely compressed and air penetration was also possible, thus reducing clothing insulation and increasing convective heat loss. This phenomenon was most likely present in our running condition with 5 m.s$^{-1}$ partly explaining the larger surface cooling at the chest. Air penetration may have occurred at the aperture of the neck (slightly larger in COLD and WBRI compared to UDI). In practical terms, a good compromise should be found as air penetration can also help evaporative cooling and avoid excessive accumulation of sweat in clothing during period of high-intensity exercise (Toftum and Nielsen, 1996).

- An extra 2 m.s$^{-1}$ frontal air velocity had a strong impact on the extent of cooling for the anterior body. This was compensated by the accentuation of hot spots over the forearms and posterior legs in the condition with less air flow. The topography of the main regions was similar with and without increased air flow.
7.5. Conclusions

The findings of the present study address the role of clothing insulation distribution on overall and regional thermal and perceptual responses. Three different clothing ensembles were tested, one having a uniform distribution of insulation (UDI) and two with a non-uniform distribution (CBRI and WBRI). CBRI was targeting “cold” regions with high insulation and “warm” regions with thin insulation and it was the opposite for WBRI.

- UDI, CBRI and WBRI produced similar responses in $T_{re}$, $T_{sk}$, $T_b$, M, HR and RPE. Regions of high and low heat loss across the body must compensate each other to obtain these similar overall outcomes. Sweat loss and sweat accumulation were larger in the heavier clothing condition (WBRI).
- Locally high insulation induced a $T_{sk}$ increase of 2 to 2.5°C irrespective of placing this insulation on naturally “warm” or “cold” regions.
- Local skinfold thickness explained the inter-individual variability in local $T_{sk}$ regardless of the clothing ensemble but not the intra-individual distribution of $T_{sk}$.
- Wearing the three clothing ensembles, $T_{sk}$ distribution was specifically different during exercise and over the anterior part of the body. Regardless of clothing configuration, some consistent features in the $T_{sk}$ pattern were still observed (Y-shapes, warmer creases, colder lower body). Circulatory heat transfers are supposed to have a strong contribution to the $T_{sk}$ patterns together with the large insulation of fat deposits and muscles of the anterior torso and upper legs.
- Local sensations were not directly linked to local $T_{sk}$ and the present results demonstrated the importance of a lower $T_{sk}$ for thermal comfort during exercise.
- High insulation targeting the back and anterior arms was beneficial at rest but became detrimental for comfort during exercise. Reducing the non-uniformity of $T_{sk}$ by targeting the naturally cold regions may have a comfort advantage during rest and exercise in the cold but this would need to be confirmed with other types of exposure.
Additional observations from various tests were also integrated into the analysis in order to understand further the role of external determinants: CLOTHING and AIR VELOCITY.

- At the same $\bar{T}_{sk}$, the $T_{sk}$ distribution was slightly different in a nude or clothed situation (hot spots at the upper chest with clothing and in the calves, posterior legs without clothing) but the overall topography of the main isotherms was identical.

- Frontal air velocity affected the extent of surface cooling over the anterior body but this was compensated by higher $T_{sk}$ over the forearms and posterior legs in a condition with less air flow. The overall topography of the main isotherms was similar with and without increased air flow.

Some practical information is relevant to clothing design and will also be discussed in Chapter 9. The main practical findings confirm the need for an approach combining cold protection and moisture management when cold weather apparel is considered for moderate to high intensity exercise.

- The manipulation of clothing insulation and its regional distribution only is not relevant whilst exercising at metabolic rates likely to elicit moderate to high sweat production. The removal of sweat and the reduction of potential wetness sensations are crucial during exercise and the subsequent recovery to avoid the after-chill especially in cold environments.

- One can assume that the optimal clothing ensemble for these conditions would have similar insulation distribution as in CBRI (even more insulated) before and after exercise, and a combination of fabrics with lower vapour and dry resistance, larger air permeability and potential opening vents during exercise.

- Over short resting periods, the benefits of the CBRI condition are promising and may be further employed in clothing systems. However, the contrasts in insulation were well pronounced and the mass market acceptability of this design would have to be studied.

- The implementation of heating elements may address the issue of “cool to cold” sensations when suddenly exposed to the environment (i.e in winter) or at the cessation of exercise. The implementation of ventilation systems
(on/off) to be activated according to the person’s need may favour heat exchange with the environment to facilitate evaporative and convective heat loss during exercise.

- The prototypes used in the present study provided garments with fixed properties. When people are facing evolutive or transient metabolic and environmental challenges, they will most likely require evolutive ergonomic systems. Behavioural adaptation with layering in the cold is a good illustration of this need.
CHAPTER 8

Conclusions

This chapter will summarise the main findings obtained from the research conducted in this thesis. The nature of the work was mainly descriptive and exploratory as the introduction specified that no extensive research has been performed in the field of $T_{sk}$ variations, specifically with regards to spatial variations with a fine resolution over the whole-body. Following the development of an original methodology using infrared thermography, the thesis has provided some insights in:

- the understanding of internal determinants dictating the $T_{sk}$ variations across the body and between individuals
- the role of external determinants mainly modifying the absolute $T_{sk}$ values and also $T_{sk}$ variations across the body
- the interaction between regional $T_{sk}$ and thermal perceptions

8.1. Determinants of skin temperature

The distinction between internal and external determinants as proposed by Houdas (1975) was useful in order to carefully design the experiments, controlling or not controlling for the influence of each determinant. As the focus was on the whole-body, it was yet impossible to fully clamp responses occurring at a systemic level. It is apparent that $T_{sk}$ is governed by a dynamic interaction between these internal and external determinants, acting on the heat exchanges between the body core and the skin as well as between the skin and the environment.

8.1.1. Internal determinants

It can be concluded that internal determinants collectively affect the spatial $T_{sk}$ variations. The present work highlighted the regional relevance of some of these internal determinants; it did not however quantify the exact relative contribution of the determinants locally. Specific interventions and imaging techniques, presented hereafter, would be required for that purpose.
8.1.1.1. Skinfold thickness and body fat content

Firstly, it is important to separate the influence of fat tissue thickness acting locally ($T_{sk,local}$) and whole-body fat content (%BF) which seems to act on a systemic level ($\bar{T}_{sk}$). In Chapter 3, the recruitment of homogeneous groups of males and females matched for age and fitness level provided answers on these two aspects. In line with the overall population, females had larger body fat content (whole-body) and larger skinfold thickness (locally) compared to males. There was a 1.8°C $\bar{T}_{sk}$ difference on average (colder for females) and $\bar{T}_{sk}$ appeared to be more correlated between individuals with metabolic heat production (lower for females) than body fat content (%BF). Moreover, the absence of a continuum in %BF between males and females prevented strong conclusion from being drawn. This was also true for SFT$_{local}$, where consistent correlations with $T_{sk,local}$ only occurred at the thigh. In Chapter 6, the hiking activity (lower heat production than running) revealed that %BF may have explained the 0.6°C $\bar{T}_{sk}$ difference on average between males and females (colder for females) with a larger %BF range and better continuum than Chapter 3. On the other hand, the local correlations again highlighted a significant relationship only for the thigh region. Other factors may be involved in the local inter-individual differences between males and females such as local anthropometry (modifying heat storage and heat loss) or local blood flow distribution (not assessed in these experiments).

In order to rule out sex-related specificities, it was important to design a study with a single sex group and this time with an increased continuum of local and global fat parameters. Chapter 4 addressed this fundamental research question with a group of 20 males (7-40%BF), also excluding the limitation of having two body fat calculations for males and females (Chapter 3). The results emphasized the significant influence of body fat both globally and locally for most body regions. Strong relationships were obtained in a situation of low heat production (rest) and intense vasoconstriction as well as moderate heat production (cycling) and various levels of blood flow redistribution (early onset of peripheral vasodilation in participants with large %BF). Interestingly, the local negative relationships ($T_{sk,local}$ vs SFT$_{local}$) were stronger, the thicker the fat deposit (e.g hip, suprailiac).

In chapter 5, the study of two air temperatures during rowing (10°C vs 20°C) revealed that the overall relationship ($\bar{T}_{sk}$ vs %BF) was true only in the cold environment. In Chapter 7, the global and most local correlations were strongly
significant during running irrespective of the clothing condition. This is in contrast with data of Chapter 3 using the same protocol in a semi-nude condition but the discrepancy might be explained by the larger range of SFT locally and %BF globally in the 12 males of Chapter 7 compared to Chapter 3.

A specific limitation should be highlighted from the above results regarding the concept of body fat content. In the present work, %BF was always estimated based on the sum of 4 to 7 SFT (Jackson and Pollock, 1978). In some studies, the negative correlations were also found between $T_{sk}$ and the sum of SFT from 24 body sites. This raises the question whether body fat content or thickness matters the most at a systemic level. We could hypothesize that thickness seems to play a very important role both locally and for whole-body responses. Yet, some studies reported the regional and overall contribution of fat content (Glickman-Weiss et al., 1996). Further investigation should integrate alternative measurement of body fat content (Dual-energy X-ray absorptiometry, underwater weighing) and our methodology to determine $T_{sk}$ in order to assess this specific issue.

In summary, body fat explained the inter-individual $T_{sk}$ variations in $T_{sk,local}$ ($SFT_{local}$) and $T_{sk}$ (%BF) with groups sufficiently heterogeneous in %BF (>10%BF range) in the cold (<10°C $T_a$) at various levels of metabolic heat production. SFT did not contribute to the sex-differences in $T_{sk,local}$ at the exception of the thigh region.

8.1.1.2. Heat production and active muscles

The five experimental chapters presented different types of activities performed at various level of metabolic heat production from about 60 W.m$^{-2}$ to 600 W.m$^{-2}$. There was yet no study doing a strict comparison of different metabolic rates using the same protocol but rather a succession of different metabolic rates (rest and exercise). This choice was made to correspond more closely to ecological conditions; moreover studies have shown that the $T_{sk}$ responses and $T_{sk}$ patterns are little affected by levels of heat production (McIntyre, 1980; Werner et al., 1985).

However, local heat production through active muscles plays a decisive role in very regional aspects of the $T_{sk}$ patterns as firstly observed using infrared thermography by Clark et al. (1977) during running. Various types of activities were therefore explored in order to understand the diversity of these discrete pattern specificities. Chapter 3 and Chapter 5 were based on the same protocol and environmental
conditions to allow for a direct comparison of running and rowing, despite the limitation of having two separate groups of males (but close characteristics). Our methodology using whole-body infrared mapping highlighted the activity-specific muscles, i.e. the upper body muscles (biceps, hand flexor and extensor, trapezius) during rowing, the lower body muscles (tibialis anterior, gastrocnemius, soleus) during running. The main hypothesis is that a direct radial vascular convection of heat from active muscles to overlying skin takes place via venous blood flow (Cooper et al., 1959) with blood circulating from deep to superficial veins (Gisolfi and Robinson, 1970). This heat dissipation was clearly visible in the limbs where tissue insulation is not maximal (thin skin and fat thickness) as well as high perfusion especially during exercise.

In Chapter 4, the $T_{sk}$ patterns during cycling (following a 60-min resting period) revealed the importance of the active thigh muscles, especially in the group with minimal fat (LF), confirming that $T_{sk}$ is indeed warmer with the combination of high heat production and low tissue insulation.

In Chapter 6, the $T_{sk}$ patterns highlighted the relatively warmer lower legs and hamstrings during both uphill and downhill walking in a clothed experiment. Similarly in Chapter 7, the importance of the active running muscles was also observed despite the presence of clothing with various insulation distribution, therefore confirming the leading regional role of local heat production in the $T_{sk}$ patterns.

Whole-body maps of glucose metabolism following running and cycling demonstrate the location of intense glycolytic activity (Iemitsu et al., 2000; Masud et al., 2009). Though the association with heat production was not discussed in these studies, the maps appeared to be in agreement with our $T_{sk}$ body maps, showing the relatively warmer skin overlying the active muscles. The method ($[^{18}F]FDG$-PET) could be very relevant to further understand the $T_{sk}$ patterns, especially towards dissociating the origin of produced heat (active muscles) from heat conveyed (by the blood flow) on a systemic level without flow intervention.

**8.1.1.3. Skin blood flow**

The vasomotor tone is mainly dependent upon autonomic control; skin blood flow can therefore vary widely with the type of environmental and metabolic challenges encountered by the human body. This active internal determinant was investigated in
situations of exercise in the cold where the metabolic blood flow demand was moderate to high, and the skin thermoregulatory demand was only moderate due to the favourable skin-to-environment gradient for heat dissipation. In Chapter 3, 5, 6 and 7, there was no measurement of skin blood flow but it can be assumed that following a short period of cold-induced vasoconstriction, participants experienced exercise-induced vasodilation in the extremities. In Chapter 4, these mechanisms were quantified in a non-acral (forearm) and acral (finger tip) regions using Laser Doppler flowmetry. Our results highlighted that $T_{sk}$ in the finger was correlated with finger tip blood flow but this was not the case in the forearm region. A quantitative determinism was therefore only found in the extremities where the range of blood flow is very large and dynamic (variations of the sympathetic vasoconstrictor tone). For other body regions, it can be hypothesized that the position, density and the depth of superficial vessels are as important as the blood flow per se. The appearance and potential role of cutaneous perforators for heat dissipation illustrate the importance of the vessel position (Hunold et al., 1992; Binzoni et al., 2004; Merla et al., 2010). It can also be assumed from the various patterns obtained in the present work, that “core” body regions are constantly highly perfused with a dense network of capillaries overlying larger vessels connected with the heart (subclavian, jugular, carotid, angular). This creates a uniform isotherm of relatively warmer $T_{sk}$ in the sternal, thyroid (upper chest), scapular (base of the neck) and orbital regions cooling less than the surrounding regions in the cold. In Chapter 3 and 7, a specific connection between perfusion of brown adipose tissue (cold activated in lean people) and relatively warmer $T_{sk}$ over the spine and supra-clavicular region has been suggested but this would require further investigation.
8.1.2. External determinants

8.1.2.1. Air temperature

The present work was limited to cool to cold exposure based on a combination of low environmental temperatures (5°C to 20°C) and different clothing status (semi-nude and clothed conditions). This choice was in line with requirements from the funding body having direct applications for cold weather apparel. Air temperature was the specific focus of Chapter 5 through a direct comparison of 8 males performing the same rowing exercise at 10°C and 20°C. A 10°C difference in $T_a$ induced a 4°C $\bar{T}_{sk}$ difference on average over the whole protocol and $T_{sk}$ patterns were little affected by $T_a$. The colder 10°C $T_a$ led to a larger $T_{sk}$ variation across the body (intra-individual) compared to the 20°C $T_a$, mainly due to the colder extremities. This was also well illustrated by others though using contact measurements and a small sample size (Werner et al., 1985) but more environmental exposure.

Interestingly, RPE was found to be lower after 40 minutes of rowing in the 10°C $T_a$ and this was associated with similar $T_{re}$ and thermal comfort but lower sweat loss, lower regional $T_{sk}$ and lower thermal sensation. This result is in line with others (Maw et al., 1993) suggesting that RPE is most sensitive to peripheral inputs ($T_{sk}$) than central factor ($T_{core}$).

8.1.2.2. Air velocity

The influence of air velocity on $T_{sk}$ has not been specifically addressed in this research work. Chapter 3, 5 and 7 were performed with 2.8 m.s$^{-1}$ frontal wind whereas Chapter 4 had no wind and Chapter 6 only a 5-min exposure to a 2.8 m.s$^{-1}$ frontal wind. The potential cooling induced by this exposure (at the cessation of exercise) in Chapter 6 was counterbalanced by clothing adjustment (addition of a fleece layer) so that virtually no change in $T_{sk}$ from pre-exposure occurred, apart from the disappearance of the backpack thermal signature.

In Chapter 7, the dataset of $T_{sk}$ patterns used to create the clothing prototypes had used different air velocity than the intervention trial. Though the comparison was based on two different male groups, the $T_{sk}$ body maps gave some evidence that the addition of 2.2 m.s$^{-1}$ (from 2.8 to 5 m.s$^{-1}$) affected the extent of anterior torso
cooling. The Y-shape of colder $T_{sk}$ was covering a larger surface, quite similar to what found in Chapter 3 on nude males running at 10°C and 2.8 m.s$^{-1}$.

**8.1.2.3. Relative humidity and radiant temperature**

As discussed in the introduction (Chapter 1), $rh$ together with $T_a$ determines the water vapour content of the air which in turn defines the evaporative cooling power of the environment. In cold conditions, large changes in $rh$ would only minimally affect this cooling power as opposed to hot environments. Due to time constraints, this parameter was not investigated.

On the other hand, radiant temperature can strongly affect $T_{sk}$ and in ecological outdoor conditions. A clear and sunny sky in autumn/winter can often be encountered in recreational sport activities. This was not explored in the present thesis. However, pilot tests in the laboratory using infrared thermography and 3 conditions of solar radiation during cycling (0 W.m$^{-2}$, 270 W.m$^{-2}$, 600 W.m$^{-2}$) showed that $T_{sk}$ in the exposed body regions was almost perfectly correlated with the solar heat load. $T_{sk}$ at the lower back was 4.5°C higher at the high intensity solar load compared to no load.

**8.1.2.4. Clothing and equipment**

Evaluating the efficiency of a body-mapping approach into clothing design was a clear goal. The development of fundamental knowledge in $T_{sk}$ varations corresponded to an important first phase before any intervention.

The association of perceptual and thermal data from Chapter 6 (hiking) was useful to quantify the issues faced by recreational hikers in a scenario mimicking real life conditions. The $T_{sk}$ patterns emphasized the discrete role of the backpack on regional $T_{sk}$ with the strongest influence in the lower back (+3°C compared to without backpack), causing uncomfortable warm and wet sensations. Despite clothing adjustment during the ascent (2 layers for the upper body to 1 layer), the environmental and metabolic conditions were such that warm discomfort occurred at the end of the uphill phase even without wearing a backpack. In females, the largest discomfort occurred during the after-chill exposure and this was associated with an intense face cooling.

In Chapter 7, the manipulation of $T_{sk}$ was successful to create three distinct $T_{sk}$ patterns with similar $\bar{T}_{sk}$: a natural clothed pattern (UDI), an accentuated natural pattern (WBRI) and a minimized natural pattern (CBRI). Targeting hot and cold
spots with high and low insulation was aimed at reducing heat dissipation (WBRI) and reducing the $T_{sk}$ contrasts between body regions to improve comfort (CBRI). There were no relevant changes in heat dissipation with WBRI and we observed a tendency towards a better comfort perceived in CBRI. The body-mapping approach therefore seems promising. However, more evidence in different controlled conditions would be required to provide clear and significant conclusions.

8.2. Patterns of skin temperature distribution

The main outcomes of the present work are illustrated by the absolute and relative body maps of $T_{sk}$ distribution. The topography of $T_{sk}$ variations was assessed in a qualitative manner in order to establish the anatomical position of “hot” and “cold” spots across the body, over time, in different conditions and for different individuals. It can be concluded that a universal $T_{sk}$ pattern exists and only a strong intervention (clothing CBRI) can partially obscure it during exercise in the cold. The resting and exercising patterns varied to a small extent when the whole-body is considered. They are presented separately with this summary of findings (Figure 8.1 and 8.2).
Figure 8.1. Summary of resting relative $T_{sk}$ patterns. A. Semi-nude females and males after 5 minutes standing at 10°C B. Semi-nude males with moderate %BF after 60 minutes of seated rest at 10°C C. Clothed (1.3 Clo) females and males (with or with no backpack NB) after 5 minutes standing at 5°C D. Clothed (0.7 Clo) males after 5 minutes standing at 5°C with three clothing ensembles (C: targeting cold regions, U, uniform insulation, W, targeting warm regions).
Figure 8.2. Summary of exercising relative T_{sk} patterns. A. Semi-nude females and males after 40 minutes of running at 70% $\dot{V}O_{2,max}$ at 10°C (2.8 m.s\(^{-1}\) wind) B. Semi-nude males with moderate %BF after 30 minutes cycling at 50% $\dot{V}O_{2,max}$ at 10°C (no wind) C. Clothed (1.3 Clo) females and males wearing a backpack after 60 minutes walking at 55% $\dot{V}O_{2,max}$ at 15°C (no wind) D. Semi-nude males after 40 minutes of rowing at 60% $\dot{V}O_{2,max}$ at 10°C (2.8 m.s\(^{-1}\) wind) E. Clothed (0.7 Clo) males after 40 minutes of running at 70% $\dot{V}O_{2,max}$ at 5°C (2.8 m.s\(^{-1}\) with three clothing ensembles (C: targeting cold regions, U, uniform insulation, W, targeting warm regions).
Some consistent features can be described in the resting patterns (Figure 8.1):

- upper body always warmer than the lower body
- clear separation between the torso and the colder arms
- specific cooling of pectorals and abdomen depending on the severity of cold exposure (e.g. prolonged exposure with no insulation in B. or thin insulation with WBRI in D.)

Some consistent features can be described in the exercising patterns (Figure 8.2) where the contrasts between regions become more pronounced, i.e the $T_{sk}$ non-uniformity is larger:

- a Y or V-shape region of colder $T_{sk}$ over the anterior torso (especially with wind)
- a Y-shape region of warmer $T_{sk}$ over the posterior torso (slightly modified by the backpack or the upper-body exercise)
- the natural body creases (elbow, popliteal fossa, orbits) warmer than the surrounding region

As highlighted in 8.1.1.2, regional variations occurred in the $T_{sk}$ patterns according to the activity-specific muscles involved in the exercise.

In Chapter 3, 4 and 7, a body-mapping approach was also used to assess the spatial variations of SFT across the body. A total of 24 body sites were assessed and then analysed with the corresponding $T_{sk}$ regions. This procedure allowed the evaluation of within-subject relationships (intra-individual) between the distribution of $T_{sk,local}$ and the distribution of $SFT_{local}$. From the different chapters, it can be concluded that the $T_{sk}$ whole-body maps were not explained by the distribution of $SFT_{local}$ neither during prolonged rest with intense vasoconstriction (Chapter 4) nor during semi-nude (Chapter 3) or clothed exercise (Chapter 7) with various levels of regional blood flow.

Interestingly, in situations where contrasts between regions were the most pronounced (nude at the end of exercise in Chapter 3 or with thin anterior insulation at the end of exercise in Chapter 7), a negative relationship between $T_{sk}$ distribution and SFT distribution was significant when only the anterior torso sites were taken into account. This also implies that the severity of cold exposure was not sufficient in Chapter 4 (semi-nude at 10°C rest with no wind) to highlight the regional SFT topography. It can also be assumed that even during running (Chapter 3 and 7), part
of the tissue insulation was provided by the pectoral and abdominal muscles, which might be a lot less perfused than the leg muscles for this weight-bearing exercise. Imaging techniques can bring more insights in the relative contribution of the several active and passive internal determinants in the $T_{sk}$ patterns. The determination of tissue insulation could be done by Magnetic Resonance Imaging (MRI) or Computed Tomography (CT), the determination of cutaneous perfusion and position of superficial vessels by Laser Doppler imaging (over large body surfaces) and the localization of heat production by 3D-PET scans.

8.3. Skin temperature and perceptions

A secondary aim of the thesis was to explore the relationship between perceptual responses and $T_{sk,local}$ once again using the original body-mapping procedure. Eleven body regions were assessed in all Chapters for thermal perceptions (thermal sensation and thermal comfort):

<table>
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<tbody>
<tr>
<td>4. Lower Back</td>
<td>8. Dorsal hands</td>
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</tbody>
</table>

From the different between-subject analysis, it was found that the number of significant correlation between perceptual votes ($T_{S_{local}}$, $T_{C_{local}}$, $T_{S_{overall}}$, $T_{C_{overall}}$) and $T_{sk,local}$ was very limited when single stages of protocols were considered. Despite $T_{sk}$ differences between sexes or between individuals with varying %BF, they had similar thermal perceptions and therefore no relationship was obtained. In other words, the inter-individual variability in both thermal perceptions and $T_{sk,local}$ was not sufficient to promote significant relationship regardless of the protocol. More significant local correlations were highlighted when several protocol stages or conditions were combined using all participants, as can be illustrated in Chapter 5 (10°C and 20°C) and Chapter 6 (after-chill exposure and descent). In Chapter 4, 6 and 7, we specifically observed that face $T_{sk}$ was a good predictor of $T_{S_{local}}$ and $T_{S_{overall}}$ over the resting, hiking and running stages of the protocol.

A within-subject analysis (across the body) was also performed thanks to the body-mapping procedure. In Chapter 3 (running), Chapter 4 (rest) and Chapter 7 (running), we demonstrated a significant positive relationship between the distribution of $T_{S_{local}}$
and the distribution of $T_{sk,local}$ at the end of exercise (Chapter 3, 7) or prolonged rest (Chapter 7) i.e when the $T_{sk}$ non-uniformity was maximal. For all other conditions, participants were not able to discriminate their $T_{Slocal}$ with relatively homogeneous $T_{sk}$. This finding was original as, to our knowledge, no other studies have performed this type of analysis (between regions) over the whole-body.

In terms of applications, these results may encourage intervention to reduce heterogeneity in whole-body $T_{sk}$ in order to avoid extreme sensations to occur. The production of a specific prototype targeting the naturally “cold” regions followed this principle (Chapter 7). The prototype (CBRI) was successful in minimizing the regional contrasts in the $T_{sk}$ patterns. The slightly improved thermal comfort, especially in the pre- and post-exercise phase, is promising for such an intervention and further investigation could highlight a stronger effect in conditions with lower metabolic heat production or stronger environmental cooling.
CHAPTER 9
Applications of Research and Future Recommendations

9.1. Applications of Research

This research was part funded by Oxylane Research, the research & development department of Oxylane, in charge of the improvements and validation of innovative sport products sold in the stores Decathlon. Oxylane Research works together with the network of 25 sport brands and 12 component brands owned by the Oxylane group, therefore covering a large variety of sport activities and technologies. The “Thermal Sciences Laboratory” guarantees the thermal comfort for all these sports clothing and equipment and the research conducted in the present thesis was in close connection with the Engineers from this laboratory. The field of bodymapping has gained strong interests in the company with the aim of combining improved comfort and integrated design whilst trying to optimize the cost of potentially innovative fabrics or technologies in the target regions. Bodymapping also attempts to tackle the issues of variations in climate or exercise intensities by providing the optimal technology locally according to the regional thermal needs in these various conditions.

The applications of the present research were directed towards improving the bodymapping solutions developed by the Oxylane sports brands. The bodymapping approach associating $T_{sk}$ and perceptual data was valuable for this purpose and it was mainly used in conjunction with other bodymapping data such as sweat mapping (Caroline Smith, PhD thesis, 2009), cold sensitivity mapping (Yacine Ouzzahra, PhD thesis, 2012) and wetness and warm sensitivity mapping (Nicola Gerrett, PhD thesis, 2012), all performed at the Environmental Ergonomics Research Centre (Loughborough University) under the supervision of Professor George Havenith. Three illustrations of applications are presented below. For confidentiality reasons, only the main transfer of knowledge will be discussed and the technical aspects of the products will not be covered.
9.1.1. Illustration 1: Kalenji Evolutiv

Chapter 3 described the thermal and perceptual responses of male and female runners in a cold environment (10°C). The results were linked to the challenges of Kalenji, the running brand of Oxylane. Their work focused on developing a garment for cold weather capable of overcoming the issues of cold discomfort during inactivity or post-run phase and warm discomfort during high intensity running. During the study presented in Chapter 3, Kalenji was finalising the development of the garment and Thomas Voelcker (R&D Engineer in the Thermal Sciences Laboratory) was responsible for implementing the mapping data from the different PhD works done in Loughborough as well as fundamental knowledge of the literature. Results about perceptual responses during running and associated $T_{sk}$ were presented to Kalenji during a meeting in Villeneuve d’Ascq (Oxylane headquarters, France). This presentation was accompanied with some suggestions about an integrated approach from mapping studies to the laboratory engineers.

The results from Chapter 3 demonstrated a good agreement between the scientific evidence and the work done by Thomas Voelcker and Kalenji based on fundamental and field knowledge.

Figure 9.1 Commercial communication of the Kalenji Isolate Evolutiv

Figure removed due to copyright
For this garment, three different types of fabrics were used with different thermal characteristics depending on the body region. A small evolutive system was developed in the shoulder region to locally improve the dry and evaporative heat loss (increased air permeability, lower dry and wet resistance) with a flap modulated on demand by the wearer. A study within the Thermal Sciences Laboratory demonstrated that this garment significantly maximised thermal comfort compared to the best commercially available reference from Kalenji.

9.1.2. Illustration 2: Quechua Air Tech Warm

In Chapter 7, there was a tendency for the protection of cold regions to be beneficial for comfort during exercise in the cold. Additional insulation over the back (WBRI) was detrimental for local comfort whereas a thin insulation over the back was better perceived by the participants. Chapter 6 described the thermal issues and their dynamics during a hiking scenario mimicking real-life conditions. It was clear that the build up of moisture in the back and armpits was responsible for both warm discomfort during hiking for males (warm and wet sensations) and cold discomfort for females (when exposed to air velocity after exercise). The $T_{sk}$ maps also revealed the global impact of the backpack in the upper and lower back as well as underneath the waist belt and shoulder straps. Sweat mapping during hiking had been performed in a consultancy between the Environmental Ergonomics Research Centre (Loughborough University) and Oxylane Research in 2005. With this knowledge in mind, the combined work of the Thermal Sciences Laboratory (Thomas Voelcker, Ying Gao, Damien Fournet) Stratermic team (componant for cold weather apparel) and Quechua team (Oxylane hiking brand) managed to develop a garment with an innovative fabric for excellent moisture management properties targeted in the back, and a good level of insulation in the anterior torso.

The laboratory team was involved in the selection of the fabric towards the validation of the final garment. Human testing was completed using a similar protocol as Chapter 6, and demonstrated a reduction of wetness sensation during moderate walking intensity and also during the after-chill exposure. A picture of the garment is presented in Figure 9.2.
9.1.3. Illustration 3: Quechua Lightshell

The study design of Chapter 6 was discussed between the Oxylane Research team and Quechua team in order to reproduce real-life conditions for recreational hikers. Quechua indeed wanted to have some quantitative data about the discomfort issues encountered during hiking and the associated thermal mechanisms involved. The results were presented to several Quechua teams linked to products such as underwear, fleece top, jackets, trousers, backpacks. Following recommendations based on these results, the team involved in trail running and underwear was keen to develop a 2-in-1 underwear (top and tights) that could provide comfort in various climatic conditions and with various exercise intensities (uphill, downhill, resting phases). A project was therefore launched with the Stratermic team in order to select the right fabrics and adjust the design to match the recommendations. Furthermore, the conclusions of Chapter 7 clearly stated that evolutive solutions are definitely required in the context of environmental and metabolic variations. A design idea that could well be integrated in this product was suggested by the author together with Emilien Mourot (Stratermic). After several prototypes, an innovative concept of evolutive sleeve was born and then industrially protected with a patent (submitted in 2012). The illustrations of the patent are presented in Figure 9.3.
The main benefit of this sleeve is that it can be adjusted on demand into 4 positions, covering the hand (to avoid cold discomfort), in a normal sleeve position, slightly open (to offer air inlet to favour internal convection), and half sleeve (to allow dry and wet heat loss with the exposed forearm whilst drying the internal fabric of the sleeve). This idea was combined with a long collar zip so that the wearer can behaviourally thermoregulate easily targeting either the arms (very favourable for heat dissipation) or sternal and thyroid regions (high heat loss as observed in the $T_{sk}$ maps).

The final ensemble (named Lightshell) was then tested on a thermal manikin in order to assess its capacity to be worn in a large range of climate, notably with the evolutive solutions. It was also compared to other trail running ensemble composed of 2 layers.
The final versions of the ensemble are currently under development. Further work will include wear trials in the field in order to validate the benefits of this pioneering solution. Quechua was missing such kind of 2-in-1 ensembles for cold weather trail running.

Duplication of the evolutive sleeve concept for other Oxylane brands are currently under progress together with Emilien Mourot, within Stratermic, who is now dedicated to finding evolutive solutions, that are more cost effective (such as the one developed here) or more technological. The concepts of bodymapping and “evolutivity” will be at the heart of many future developments and this thesis can represent a good evidence of these requirements.

On top of the above illustrations, the numerous regional and overall thermal data presented in the thesis have fed the multi-segmental model of human thermoregulation and clothing heat transfers computed by Dr. Bernard Redortier within the Thermal Sciences laboratory. The data obtained in various climatic conditions and metabolic rates are helpful to validate the outcome of the manikin running in thermophysiological mode. Moreover, the resolution of the $T_{sk}$ maps may also be sufficient to validate high-resolution thermoregulatory models currently being developed (e.g. voxel model by ThermoAnalytics).

Finally, the methodology developed in the thesis with the production of $T_{sk}$ body maps and the automatic segmentation of regions of interest is currently used or adapted to specific research questions in the R&D department. This varies from evaluating the topographical influence of cooling or heating technologies to quantifying local warming due to clothing friction.
9.2. Recommendations for future research

This thesis was mainly focused on the development of detailed knowledge in $T_{sk}$ variations for different types of individuals, different climatic and clothing conditions, different types of activities. This was associated with an analysis of the link between regional thermal perceptions and regional $T_{sk}$. Several research questions or areas of interest were not covered and may deserve further investigation.

9.2.1. Understanding of the $T_{sk}$ patterns

The different internal determinants of $T_{sk}$ have been well defined. From a modelling prospective, it will be useful to examine the relative contribution of these determinants in the $T_{sk}$ patterns either by controlling them locally or by assessing them all simultaneously. Blood flow could be controlled pharmacologically or by limb occlusion, heat production could be controlled with localised muscle contractions, potentially one-sided to observe the contralateral hemodynamic changes. Some of these interventions have been performed with contact measurements but not extensively with infrared thermography. Recent advances in medical imaging techniques may provide the resolution to separately quantify muscle/fat/skin thickness, local heat production (from muscles, brown adipose tissue?), local blood flow and therefore extend the understanding of the $T_{sk}$ patterns.

Cutaneous perforators have been well identified in the $T_{sk}$ patterns and seem to play role in heat dissipation during exercise. It would be of interest to explore the specific dynamics and localisation of these perforators in connection with the overall vasomotor changes during exercise depending on the activity and climate. This exploration would require a higher resolution thermal camera than the one used in the present thesis.

Regarding external $T_{sk}$ determinants, it will be important to quantify the role of solar radiation (intensity and direction) and also wind direction on the $T_{sk}$ patterns so that all types of outdoor conditions could be modelled. Moreover, the influence of clothing with different insulation distribution remains to be investigated in more severe cold conditions, with potential benefits in the maintenance of $T_{core}$ or comfort benefits in situations with low metabolic heat production below the sweating threshold.
9.2.2. The research about thermal perceptions

Behavioural thermoregulation is the most effective way to regulate the body temperature. This is closely related to thermal perceptions. In the present thesis, subjective assessment was performed following a fixed procedure at standardised intervals, therefore promoting both a large inter-individual variability of perceptions and inter-individual variability of thermophysiological responses. In the context of applied research, it may be useful to be aligned with behavioural adjustments as markers of thermal discomfort instead of implementing the necessary bias of asking a question that will in turn modify the psychological state of the participant.

Exercising protocols could be designed to offer several avenues to behaviourally thermoregulate (heating or cooling by conduction, convection, radiation, evaporation) freely targeting chosen body regions on demand. Verbalisation may partly replace the use of rigid thermal questionnaires. This type of protocol may be valuable to understand further the origins of discomfort, especially helpful in the development of evolutive systems. However, this would not necessarily be valuable for comparisons between interventions or clothing conditions where assessments at regular intervals may be a better option.

9.2.3. Future directions for infrared bodymapping

The methodology developed in the present work may be useful for many types of applications. Various “normal” or “asymptomatic” patterns have been registered, mainly in exercising conditions. It could be of interest to develop a larger database including “symptomatic” responses using $T_{sk}$ body maps. Circulatory diseases or syndromes have been well documented, also using infrared thermography, but not using a standardised and averaged format that may have pedagogic value.

The infrared mapping method can also be used for applied research in the evaluation of heating or cooling solutions implemented in equipment or clothing. It could easily quantify the magnitude and topographical impact of an intervention in association with the perceptual benefits. For certain technologies, the efficiency compromise between surface and target regions remains to be elucidated.

The integration of the different bodymapping approaches (temperature, sweat, cold/warm/wetness sensitivities) could become a topic for modelling purposes in tight connection with garment research using these type of outputs. Target regions could be better defined depending on the type of activity, fitness level and climate.
References


Parsons, K. C. (2002). The effects of gender, acclimation state, the opportunity to adjust clothing and physical disability on requirements for thermal comfort. *Energy and Buildings, 34*(6), 593-599.


Yao, Y., Lian, Z., Liu, W., & Shen, Q. (2007). Experimental study on skin temperature and thermal comfort of the human body in a recumbent posture under uniform thermal environments. *Indoor and Built Environment, 16*(6), 505-518.


Appendix A

10. PHYSIOLOGICAL AND PERCEPTUAL RESPONSES IN COLD CONDITIONS

10.1. INFORMED CONSENT FORM

10.2. (to be completed after Participant Information Sheet has been read)

The purpose and details of this study have been explained to me. I understand that this study is designed to further scientific knowledge and that all procedures have been approved by the Loughborough University Ethical Advisory Committee.

I have read and understood the information sheet and this consent form.

I have had an opportunity to ask questions about my participation.

I understand that I am under no obligation to take part in the study.

I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.

I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others.

I agree to participate in this study.

Your name  

Your signature  

Signature of investigator  

Date
Appendix B
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.)

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<thead>
<tr>
<th>Question</th>
<th>Yes</th>
<th>No</th>
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<tbody>
<tr>
<td>1 At present, do you have any health problem for which you are:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) on medication, prescribed or otherwise</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>(b) attending your general practitioner</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>(c) on a hospital waiting list</td>
<td>Yes</td>
<td>No</td>
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<td>2 In the past two years, have you had any illness which required you to:</td>
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<tr>
<td>(a) consult your GP</td>
<td>Yes</td>
<td>No</td>
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<tr>
<td>(b) attend a hospital outpatient department</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>(c) be admitted to hospital</td>
<td>Yes</td>
<td>No</td>
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<td>3 Have you ever had any of the following:</td>
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<td>(a) Convulsions/epilepsy</td>
<td>Yes</td>
<td>No</td>
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<tr>
<td>(b) Asthma</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>(c) Eczema</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>(d) Diabetes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>(e) A blood disorder</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>(f) Head injury</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>(g) Digestive problems</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>(h) Heart problems</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>(i) Problems with bones or joints</td>
<td>Yes</td>
<td>No</td>
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Question 3 continued

(j) Disturbance of balance / co-ordination
(k) Numbness in hands or feet
(l) Disturbance of vision
(m) Ear / hearing problems
(n) Thyroid problems
(o) Kidney or liver problems

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<th>Yes</th>
<th>No</th>
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Thank you for your co-operation!

Declaration Of Consent

I, ........................................................................ hereby volunteer to be an experimental subject in thermal experiments during the period From ........../.........../ 20….. to .........../............./ 20 ..... 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 C

Scales and Colour coding

The choice of an optimal colour coded scale is highly important insofar as infrared imaging relies both on a quantitative as well as a qualitative interpretation. It is relatively easy to misinterpret the reading of 2 juxtaposed infrared images with a similar colour code but different higher and upper limits. In the present work, these limits have been chosen based on the overall range of data (from all studies) and most importantly they have been kept consistent throughout each result section. It is therefore possible to visually compare infrared maps obtained in Chapter 3 and Chapter 7 for instance.

Regarding the absolute colour scale, the choice of colours has been dictated by the classical representation of blue as a cold colour and red as a warm colour. This scale corresponds to a default scale implemented in Matlab © and called “jet” colormap. The higher limit was set at 36°C and the lower limit at 12°C.

Regarding the relative colour scale, it has been specifically designed for the purpose of this work using colormap editor within Matlab © (for more information, see http://www.mathworks.fr/fr/help/matlab/ref/colormapeditor.html). A value of 1 was required to be clearly highlighted as it represents the mean skin temperature. Shading of blue and purple colours was chosen inspired by the created scale for normalised sweat mapping from Smith & Havenith (2010). This feature allows the establishment of a clear consistency within the body-mapping approach, when dealing with normalised or relative values, in this case about two specific thermoregulatory parameters.
Infrared Mapping using Matlab ©

The overall procedure for infrared mapping is presented in the schematic diagram below.

The detailed procedure requires training and can be requested from the author at the following addresses: damien.fournet@oxylane.com or to.damienfournet@gmail.com or G.Havenith@lboro.ac.uk

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