Body mapping of perceptual responses to sweat and warm stimuli and their relation to physiological parameters

Nicola Gerrett

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Abstract

Regional differences in sweat gland output, skin temperature and thermoreceptor distribution can account for variations in regional perceptions of temperature, thermal comfort and wetness sensation. Large cohorts of studies have assessed these perceptual responses during sedentary activity but the findings are typically applied to a multitude of conditions, including exercise. However, increases in sweat gland output, redistribution of blood flow and changes in skin and core temperature are basic responses to exercise in most conditions and these ultimately influence our perceptual responses. The primary aim of this thesis is to determine factors that influence regional differences in thermal sensation, thermal comfort and wetness sensation during exercise in moderate to hot conditions. The secondary aim is to develop and understand an additional variable, galvanic skin conductance (GSC) that can be used to predict thermal comfort and wetness sensation.

The aim of the first study (Chapter 4) was to determine the influence of exercise on thermal sensitivity and magnitude sensation of warmth to a hot-dry stimulus (thermal probe at 40°C) and assess if any gender-linked differences and/or regional differences exist. From the data, body maps indicating sensitivity were produced for both genders during rest and exercise. Females had more regional differences than males. Overall sensitivity was greatest at the head, then the torso and declined towards the extremities. The data showed that exercise did not cause a significant reduction in thermal sensitivity but magnitude estimation was significantly lower after exercise for males and selected locations in females. The cause of a reduced magnitude sensation is thought to be associated with exercise induced analgesia; a reduction in sensitivity due to exercise related increases in circulating hormones.

As the literature suggests that thermal comfort in the heat is influenced by the presence of sweat, the next study and all proceeding studies were concerned with this concept. In Chapter 5, building on earlier studies performed in our laboratories, the influence of local skin wettedness (w_{local}) on local thermal comfort and wetness sensation was investigated in a neutral dry condition (20.2 ± 0.5°C and 43.5 ± 4.5% RH) whilst walking (4.5 $\mathrm{km \cdot hr^{-1}}$). Regional differences in w_{local} were manipulated using specialised clothing comprised of permeable and impermeable material areas. Strong correlations existed between local thermal comfort and local wetness sensation with the various measured w_{local} ($r^2>0.88$, $p<0.05$ and $r^2>0.83$, $p<0.05$, respectively). The thermal comfort limit was defined as the w_{local} value at which the participants no longer felt comfortable. Regional comfort limits for w_{local} were identified (in order of high-low

sensitivity); lower back (0.40), upper legs (0.44), lower legs (0.45), abdomen (0.45), chest (0.55), upper back (0.56), upper arms (0.57) and lower arms (0.65).

The maximum degree of discomfort and wetness sensation experienced during the investigation was kept deliberately low in an attempt to determine the threshold values. Therefore comfort scores and wetness scores rarely reached a state of ‘uncomfortable’ or ‘wet’ so the next step was to assess these relationships when sweat production is high and the sensations worsened. However, pilot testing indicated that a ceiling effect would occur for w_{local} at high levels of sweat production whilst thermal discomfort increased indicating w_{local} was not the determining parameter in that case. Thus an additional parameter was required. The chosen parameter was galvanic skin conductance (GSC) due to its alleged ability to monitor pre-secretory sweat gland activity, skin hydration and surface sweat.

In Chapter 6, the reliability, reproducibility and validity of GSC were confirmed in a series of pilot tests. Moderate to strong correlations were found between GSC and regional sweat rate (RSR) ($r^2>0.60$, $p<0.05$) and w_{local} ($r^2>0.55$, $p<0.05$). The literature suggests standardising GSC relative to a minimum and maximum GSC value; however uncertainties arise when attempting to achieve maximum GSC. Therefore a change from baseline (ΔGSC) was chosen as the proposed method of standardisation for further use. Additional results (from Chapter 9) revealed that ΔGSC also reflects pre-secretory sweat gland activity as it increased prior to sweat being present on the skin surface and prior to an increase in RSR. ΔGSC had a moderate to strong linear relationship with RSR ($r^2>0.60$, $p<0.05$) and w_{local} ($r^2>0.55$, $p<0.05$). In Chapter 9, also hydration of the stratum corneum was measured using a ‘moisture meter’ and the results revealed that it has an upper limit; indicating maximal hydration. From this point of full skin saturation ΔGSC and RSR markedly increase though sensations did not. It was also found that ΔGSC is only influenced by surface sweat that is in direct contact with the electrode and is not influenced by sweat elsewhere on the skin surface between electrodes.

Higher levels of thermal discomfort have rarely been explored and neither has its relationship with w_{local}. The ability of ΔGSC and w_{local} to predict local thermal comfort and wetness sensation were compared in two different conditions to elicit low and high sweat production. Unlike Chapter 5, the body sites were not manipulated to control w_{local} but allowed to vary naturally over time. The test was carried out on males (Chapter 7) and females (Chapter 8) to compare any gender linked differences and the results suggest that females are more sensitive than males to the initial presence of sweat. For both genders, w_{local} and ΔGSC are strong predictors of thermal comfort and wetness sensation. More importantly, w_{local} can only be used to predict local thermal comfort in conditions of low sweat production or low levels of thermal discomfort. However, once sweat production increases and thermal discomfort worsens ΔGSC (and not w_{local}) can predict thermal comfort. It appears that epidermal hydration has an important role on influencing thermal comfort. Receptors influencing our perceptual responses are located in the epidermis and when sweat is produced and released onto the skin surface, this epidermis swells and the sensitivity of receptors are said to increase. w_{local} indicates the amount of moisture present on the skin surface, yet ΔGSC indicates presecretory sweat gland activity and epidermal hydration where the receptors are located. This may explain why on numerous occasions thermal comfort had a stronger relationship with ΔGSC than w_{local}.

Where Chapter 5 indicated the true local comfort limits for each respective zone, Chapter 7 and 8 provided a global picture of how local regions interact and influence local thermal comfort across the body. When w_{local} varies naturally, the torso areas naturally produce more sweat than the extremities and it seemed that these areas produce so much more sweat than the extremities that they dominate local thermal comfort across the whole body. This is referred to in this thesis as a model of segmental interaction.

As with thermal comfort, wetness sensation had strong relationships with w_{local} and ΔGSC. The results also revealed a strong relationship between wetness sensation and thermal comfort. In contrast to the widely supported claim, a drop in skin temperature is not required to stimulate a wetness sensation. The point at which we detect sweat and when it becomes uncomfortable occurs at different w_{local} values across the body.

Statement

The work presented in this thesis was part funded by the Department of Human Science, Loughborough University and Oxylane research, a research and design department for the French sports clothing manufacturing company Decathlon. The data collected in this thesis was used by Oxylane research in the assessment and design of a range of their clothing.

Study 1 (Chapter 3) was conducted jointly by the author and Mr S. Hobbs (male participants) and Miss S. Coleby (female participants). The study was also done in joint partnership with Mr Y. Ouzzahra who completed a similar study with a cold stimulus. The author was responsible for assisting with the supervision of Mr S. Hobbs and Miss S. Coleby as part of their dissertation projects. The author reanalysed the raw data obtained in this study for inclusion of this thesis. The other studies were performed solely by the author.

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Publications

Conference proceedings

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Symbols and Abbreviations

a_c	*areas of control material (cm^2)*
%BF	percentage body fat (%)
C	convective heat loss per unit are ($W \cdot m^2$)
Ca^{2+}	Calcium
Ce	water vapour concentration of the environment (kPa)
Cl^-	Chloride
Csk	water vapour concentration of the skin (kPa)
Csk,s	saturated water vapour concentration of the skin (kPa)
D1	sweat travelling through the duct within the skin.
Db	body density (g/cc)
E	evaporative loss per unit are ($W \cdot m^2$)
E2	hydration of the stratum corneum
E_{max}	maximal evaporation potential per unit area ($W \cdot m^2$)
E_{vap}	actual evaporative loss per unit area ($W \cdot m^2$)
EX1	first exercise stage (30% $\dot{V}O_{2max}$)
EX2	second exercise stage (50% $\dot{V}O_{2max}$)
EX3	third exercise stage (70% $\dot{V}O_{2max}$)
GSC	Galvanic skin conductance (µS)
$GSC_{\%max}$	Percentage of its maximum: Galvanic skin conductance (%)
GSC_0	Initial value of galvanic skin conductance (µS)
GSC_{ix}	raw value of obtained from the subject (i) in a given situation (x)
GSC_{max}	maximum galvanic skin conductance obtained (µS)
GSC_{min}	minimum galvanic skin conductance obtained (µS)
GSC_{raw}	raw value of galvanic skin conductance (µS)
GSC_{std}	Galvanic skin conductance standardized relative to its minimum and maximum value (µS)
ΔGSC	Galvanic skin conductance measured as a change from baseline (µS)
GSL	Gross sweat loss (g, $g \cdot m^2 \cdot h^{-1}$)
HYD	Epidermal hydration (uA)

K	conductive heat transfer per unit area (W·m^2)
K^+	Potassium
L	external load (kg)
M	rate of metabolic energy production (W or W·m^2)
M_r	metabolic cost of running (W)
M_w	metabolic cost of walking (W)
P-EX1	first 10 minutes of post exercise
P-EX2:	last 10 minutes of post exercise.
R	radiative heat loss per unit area (W·m^2)
R1	rest in neutral conditions,
R2	rest in hot conditions,
RH	relative humidity (%)
RSL	regional sweat loss (g, g·m^2·h^{-1})
S	rate of heat storage per unit area (W·m^2)
SA	*surface area (m^2)*
SD1	sweat production within the gland.
SR	sweat rate (g·m^{-2}·h^{-1})
$STTS_s$	steady state thermal sensitivity
t	time duration of experiment (sec)
t	time, duration of pad application (sec)
T_a	ambient temperature (°C)
T_b	body temperature (°C)
TC	*t*hermal comfort
T_c	core temperature (°C)
TS	thermal sensation
T_{sk}	*s*kin temperature (°C)
TTS_s	transient thermal sensitivity
V	speed of walking (m.s-1)
$\dot{V}O_{2max}$	maximal oxygen uptake (ml·kg·min^{-1})
w	skin wettedness (dimensionless)
W	mechanical work (W·m^2)

w_b	body weight of subject (kg)
w_{b2}	body weight at the end of experiment (kg)
w_{bi}	body weight at the start of experiment (kg)
w_c	weight of control material (g)
w_d	dry weight of material (g)
w_d	dry weight of pad (m^2)
w_{local}	local skin wettedness (dimensionless)
WS	Wetness sensation
w_w	wet weight of pad (g)
η	terrain factor (η= 1.0 for treadmill)
♀	Male
♂	Female

Chapter one

Introduction

Introduction

Alongside having aesthetic appeal, sports clothing must be suitable for the sporting event and the environmental conditions likely to be exposed to in order to optimise thermoregulation and maintain wearer comfort. To have the competitive edge over other sports clothing companies, it is important that designers consider both of these factors and it is the latter that this thesis will focus upon.

A large body of research exists to understand the physiological responses, such as sweat loss and vasomotor response to exercise in hot or cold conditions and the findings are well documented. However, behavioural responses, such as clothing choice, shelter or modifying metabolic heat production are more efficient ways of maintaining thermal balance and have received comparatively little attention. The behavioural responses themselves are initiated by the perception of surrounding temperatures and a person will actively change their behaviour in order to feel thermally comfortable.

The perception of temperature is detected by the stimulation of thermoreceptors that are located around the periphery and core. However, thermal comfort and wetness sensation have no definable sense organs and are therefore open to interpretation. Thermal sensation, thermal comfort and wetness sensation have been reviewed in the literature but large discrepancies exist between findings which are typically related to the subjective nature of the research.

Regional differences in thermoreceptor distribution, skin temperature and sweat loss have given rise to an increasing number of studies aiming to determine regional sensitivity to various stimuli across the body. However, much of the research is limited to sedentary activity but frequently used by modellers in manikin studies to predict thermal comfort during exercise. The physiological changes that occur as a result of exercise, particularly in the heat may alter regional sensitivity to rising skin temperatures and rising sweat production. There is a need to establish the influence of exercise on perceptual responses and determine regional differences in sensitivity to both heat and sweat. This information could then be used more accurately by modellers and manikin users to inform the design of sports clothing and protective garments.

A joint proposal was put forward by Loughborough University and Oxylane Research; a research and design department for the French sports clothing manufacturing company Decathlon. The main aims of the project were to assess factors influencing perceptual responses (thermal comfort, wetness sensation and thermal sensation) during exercise in the heat and determine regional sensitivity across the body. The information gathered from this research project will be used by the research and development engineers of Oxylane Research to design sports clothing that promotes thermoregulation and optimises thermal comfort for the wearer. Therefore an applied approach to this research was adopted.

The topics dealt with in this thesis include regional sensitivity to hot thermal stimulation during rest and exercise; gender differences in perceptions of heat and sweat and regional differences in thermal comfort in response to the presence of sweat. Also, the link between these subjective measurements and objective parameters was looked at In designing the research project an alternative measurement variable (to traditional thermoregulatory measurements) was introduced for use in this field; galvanic skin conductance (GSC), which required more fundamental investigations.

Chapter two

Literature review

2 Literature review

2.1 Heat balance

The human body regulates core temperature (T_c) within a small range around 37°C in order to maintain health, optimise performance in everyday activities and in extreme cases prevent permanent health damages or even death. Through external and personal mechanisms the human body is able to maintain ‘thermal balance’ – where heat produced from the body is balanced with the heat removed away from the body. This dynamic equilibrium is easily explained by the conceptual heat balance equation (Parsons, 2003);

$$\boldsymbol{M - W = E + R + C + K + S}$$

Where:

M	metabolic rate ($\mathrm{W{\cdot}m^2}$)
W	mechanical work ($\mathrm{W{\cdot}m^2}$)
K	conduction ($\mathrm{W{\cdot}m^2}$)
C	convection ($\mathrm{W{\cdot}m^2}$)
R	radiation ($\mathrm{W{\cdot}m^2}$)
E	evaporation ($\mathrm{W{\cdot}m^2}$)
S	heat storage ($\mathrm{W{\cdot}m^2}$)

M-W represents the heat generation of the body and is the sum of any remaining unused energy that is converted to heat within the body (Parsons, 2003). A net heat gain will result in an increase in body temperature (and vice-versa for a net heat loss). The subsequent part of the equation indicates the mechanism whereby thermal balance can be achieved. Heat loss via conduction is the direct transfer of heat by vibrations at molecular level through a solid or liquid. Conduction is important in thermoregulation to help dissipate heat within the core to the environment via the skin. Additionally, heat can be gained from external sources from the skin which is then transferred to the core. Convective heat loss occurs in response to fluid or air movement across a surface resulting in heat exchange. There are two types of convection; forced and natural. Natural convection is the transfer of heat energy as a result of a temperature gradient. For example, heat is gained by the skin when ambient temperature (T_a) exceeds skin temperature (T_{sk}). Forced convective heat loss occurs most commonly in the form of wind or water. Convective heat loss is affected by the surface area of the object, the temperature gradient and the air speed. An additional form of convective heat loss is in the form of 'dry heat loss' which occurs at the lungs. Cool air from the environment is inhaled and heated to body core temperature in the lungs and then exhaled (Parsons, 2003). Heat can also be lost or gained via radiation in which a surface emits heat and there is a net heat flow from a hot to a cold object (Parsons, 2003). Evaporative heat loss occurs when heat from the skin is sufficient to change water into vapour. Evaporative heat loss varies between and within individuals, but a constant form of evaporative heat loss is that from 'insensible perspiration' (Kuno, 1956). The evaporation of sweat requires 2430 Joules per minute for every 1g of sweat.

A combination of these parameters outlined above provides a heat storage (S) value and if this is equal to 0 then the body is in a state of thermal equilibrium. Air temperature, radiant temperature, relative humidity (*RH*) and air movement indicate the external factors influencing the mechanisms highlighted above. Personal factors that influence the thermal balance include metabolic rate and clothing.

2.2 Thermoregulation

It is widely accepted that the preoptic anterior hypothalamus is the central thermal controller for the body (Parsons, 2003). Sensory input from various thermoreceptors located at the periphery and central locations provide information on the body's thermal status. Research by Nadel et al. (1971) indicated the relative importance of central and peripheral thermoreceptors in the regulation of temperature with a 9:1 ratio of T_c and T_{sk}, respectively. When stimulated, the anterior hypothalamus sends signals to initiate a set of physiological responses to regulate T_c. In warm conditions, where heat loss is required, the anterior hypothalamus signals for the dilatation of blood vessels, which redirects skin blood flow (*SkBf*) from the core to the periphery for heat loss via conduction, convection and radiation at the periphery. Sweat glands are stimulated to initiate/increase sweat production to lose heat via evaporation. An increased *SkBf* near the skin also transports fluid to the sweat glands for the secretion of sweat to the skin surface. When T_c and T_{sk} rise, sweat glands are activated to increase the production of sweat. Heat is lost as sweat lying on the skin surface is evaporated, which in turn cools the skin down and the blood close to the surface. As a result, blood flowing back to the core is cooled and thus attempts to lower T_c. The evaporation of sweat is the most dominant method of heat loss during exercise (Kerslake, 1972) and sweat rates of up to 1 $l \cdot hr^{-1}$ have been reported when exercising in the heat (Brake and Bates, 2003). Research by Thoden et al. (1994) found that as T_c increases, *SkBf* and sweating increase proportional to the rise in $\mathrm{T_c}$, which continues until thermal balance is achieved.

When T_c is low, the body must conserve heat through vasoconstriction, shivering and piloerection. Vasoconstriction reduces the blood flow near the surface of the skin, so to keep warm blood near the core. Shivering increases metabolic heat production via voluntary or involuntary small and rapid muscle contractions. Piloerection, otherwise known as ‘goose bumps’ is the mechanism that aims to reduce heat loss by tiny muscle contractions that cause the hairs on the body surface to stand on end (Parsons, 2003). This process reduces heat loss by maintaining a layer of still air between the body and the environment, alongside increasing metabolic rate (Parsons, 2003). Despite this, its influence of heat exchange is minimal and behavioural adaptations have a much greater influence.

2.3 Skin structure

The skin is the largest organ as it covers approximately 2 m^2 of the human body and weighs approximately 4.5-5 kg (~16% of total body weight). It acts as a barrier between the external environment and the internal environment of the human body as it protects the body from harm, helps maintains T_c through heat exchange and provides sensory information about the surroundings. The structure of the skin supports the mechanisms involved in thermoregulation, sensory perceptions and acts as a defence mechanism. The skin is comprised of two main layers; the epidermis and the dermis (Figure 2.1a). The epidermis is the most superficial layer and consists of stratum corneum (horny layer), the stratum granulosum (granular cell), stratum spinosum (spinous or prickle cell layer) and stratum basale (basal cells). There is a continual generation of epidermal cells where healthy living cells gradually move to the surface of the skin (from the basal cell towards the transition cells) where they die and form a protective layer (horny cell) until they fall off (Parsons, 2003). The dermis is the connective tissue compartment and provides pliability, elasticity and tensile strength. Various types of sensory receptors reside in the dermis that respond to temperature, pressure, movement, pain, itch and tickle which provides sensory information about the surroundings. Sweat ducts are also located in the dermis, which along with thermoreceptors, aid thermoregulation. Underneath the dermis is a subcutaneous layer (adipose tissue in Figure 2.1a), which contains several sweat glands, hair follicles, fine muscle filaments and blood vessels (Li, 2001). This general structure varies across the body depending upon location and function of the skin. The distribution of hair, density and type of receptors and blood supply vary according to location.

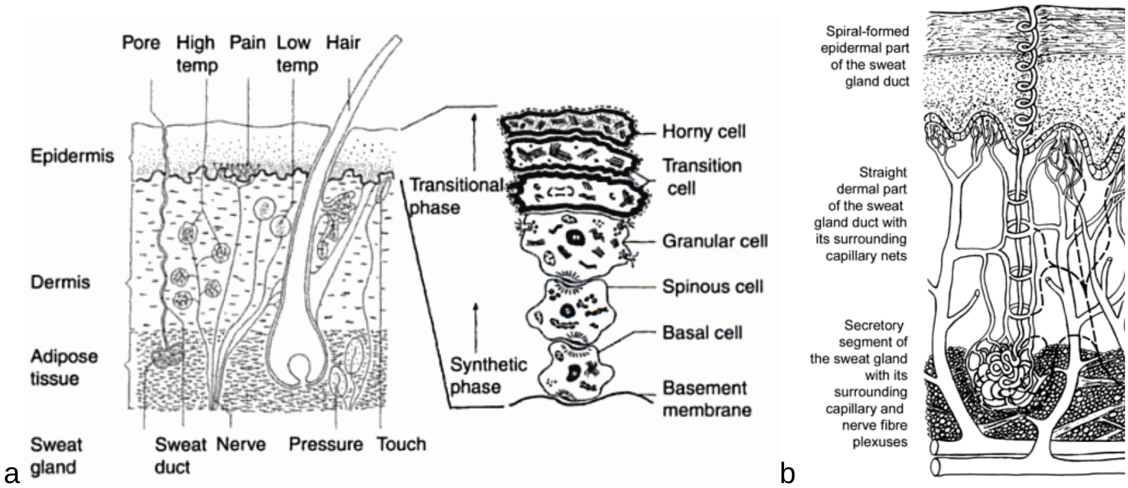


Figure 2.1: a) The structure of the human skin (Parsons 2003); b) The structure of the sweat gland and the supply of blood vessels. The efferent sympathetic innervation is indicated by the dashed line (Boucsein, 2011).

2.4 Sweating

Evaporation of sweat is the most dominant method of heat loss during exercise or when exposed to warm conditions. It is unsurprising then that sweat has a strong influence on thermal comfort, which will be discussed later in detail in this literature review. The structure and function of sweat glands will first be discussed in brief.

2.4.1 Sweat glands

It has been estimated that there are approximately 2-5 million sweat glands across the body (Kuno, 1956; Szabo 1962). The sweat glands are classified into one of three types; apocrine, eccrine and apoeccrine glands. Apocrine glands are located in limited areas such as the forehead, axilla, hands, feet and pubic regions and are stimulated by psychological stimuli such as arousal and anxiety (Sato et al., 1989a;b). Eccrine sweat glands are distributed all over the body and they are stimulated by thermoregulatory mechanisms such as an increase in T_c or T_{sk} (Sato et al., 1989a;b; Nadel et al. 1973). Apoeccrine sweat glands are a hybrid between apocrine and eccrine sweat glands but are only located in the axilla following puberty. Due to their role in thermoregulation, this report will focus upon eccrine sweat glands. The sweat gland structure (see Figure 2.1b) consists of tubular epithelium cells comprised of three main portions; the secretory coil, the duct and the intradermal spiralled duct (acrosyringium) (Edelberg, 1972). The secretory coil is located underneath the dermis in the subcutaneous layer, along with hair follicles, fine muscle filaments and blood vessels (Li, 2001). The gland extends into the duct, which is comprised of two parts; firstly the coiled duct which is located in the hypodermis (layer between dermis and subcutaneous fat layer) and secondly the straight duct which extends through the dermis. The distal portion of the duct connects to the acrosyringium which is a spiralled duct that opens onto the skin surface (Sato et al. 1989a;b). The glands become active in response to rises in T_c and or T_{sk} (McCook et al. 1965; Nadel et al. 1971) and are primarily stimulated via the release of the neurotransmitter acetylcholine from cholinergic sudomotor nerves which bind to receptors on the gland (Randall and Kimura, 1955, cited in Shibasaki et al. 2006, p.1693). Once it has bound to the receptors, intracellular calcium (Ca^{2+}) concentration increases, which causes an increase in permeability of potassium (K^+) and chloride (Cl^-) channels and causes the release of an isotonic precursor fluid from the secretory cells (Sato et al. 1989a;b). This is referred to as the pre-secretory sweat gland activity. The fluid then passes along the duct and, en route to the skin surface, NaCl is reabsorbed into the ductal walls. As a result, the sweat that appears on the skin surface is hypotonic relative to plasma. However, before sweat is released onto the skin surface, a process known as corneal hydration occurs in which the sweat penetrates the acrosyringium due to a build up of pressure and diffuses into the stratum corneum. According to Kligman (1964, cited in Edelberg, 1972) the stratum corneum is very hygroscopic, in that it can hold up to 70% of its own weight in water. It has been postulated that the corneum hydrates first before sweat is released onto the skin surface (Boucsein, 2011).

Regional differences in sweat production exist and this is typically associated with the distribution and number of active sweat glands and the output of sweat from each gland. Kuno (1956) found that the palm and sole have the greatest amount of sweat glands, followed by the head and much fewer on the extremities and the trunk. However, Smith and Havenith (2011, 2012) found that the torso had the highest sweat rates, particularly the mid-centre line of the back in males (see Figure 2.2). The results suggest that regional distribution does not correspond with eccrine sweat gland density but is likely to be associated with the number of active sweat glands and output per gland. Havenith et al. (2008) reported that despite females producing ~10% less sweat than males (420 ± 114 $g{\cdot}m^{-2}{\cdot}h^{-1}$ and 474 ± 80 $g{\cdot}m^{-2}{\cdot}h^{-1}$, respectively) for a similar relative work load, regional sweat rate follows a similar pattern to males with the central back having the highest sweat rates than other zones, whilst the lower front, arms, sides and shoulders have the lowest.

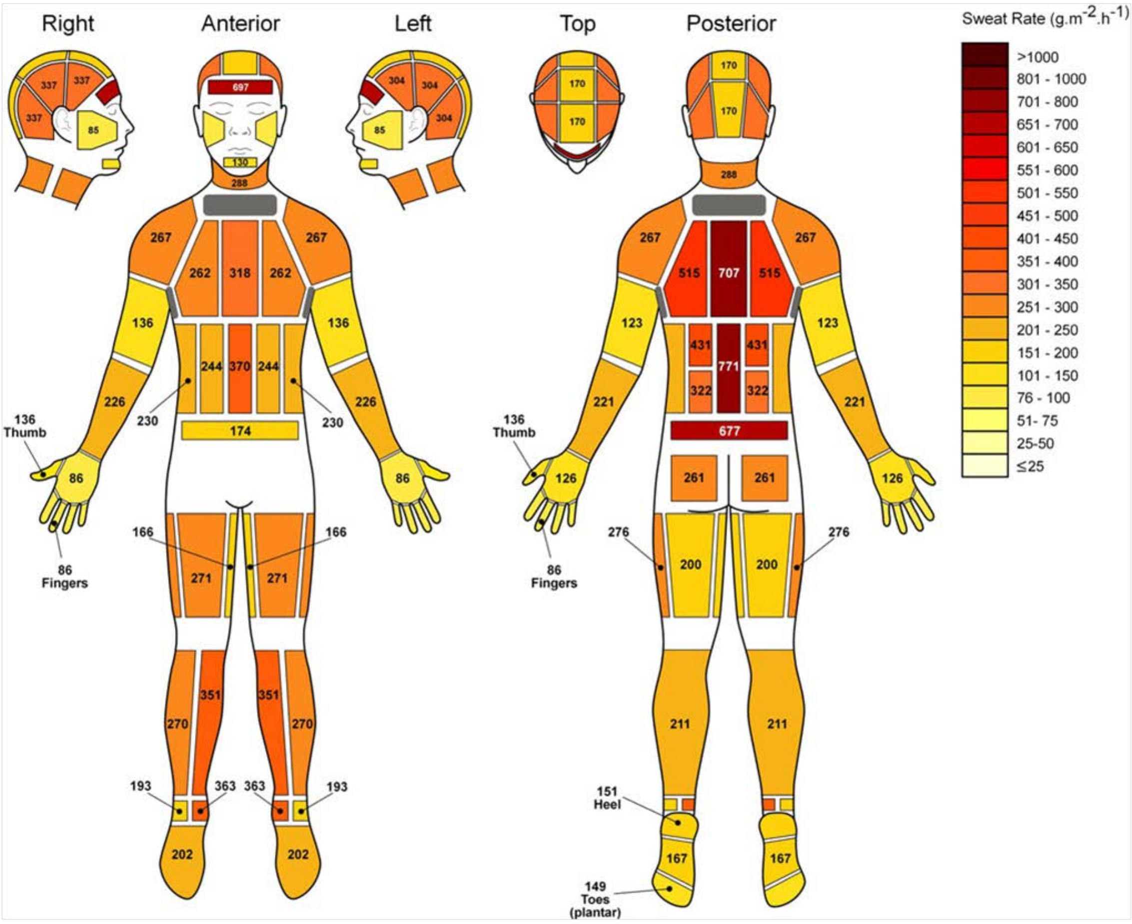


Figure 2.2: Absolute regional median sweat rates ($g{\cdot}m^{2}{\cdot}hr^{-1}$) of male (n=9) participants exercising at 55% VO_{2max} (Smith and Havenith, 2011).

2.5 Human perceptions

Behavioural thermoregulation reduces the need for autonomic thermoregulation as humans make conscious decision to change their thermal status due to emotional feelings of thermal comfort or discomfort (Li, 2001). This usually involves taking off or putting on clothing, moving into shaded areas, or adjusting indoor temperatures, suggesting that our sense of temperature change is the primary response. As a result there is a plethora of research regarding thermal perceptions which include thermal sensation, thermal comfort and sweat sensations, all of which are subjective responses. Numerous researchers have attempted to define thermal sensation and thermal comfort, the thresholds and interactions and whether they are influenced by T_{sk}, T_c or T_a (Hensel, 1981 (cited in Li, 2001, p.58); Gagge et al. 1969b; Fanger, 1970). Each of these perceptions, and the factors influencing them, will be addressed in this section.

2.5.1 Thermoreceptors

The skin is densely populated with various types of sensing receptors of which there are two types; corpuscular and noncorpuscular (free nerve) endings. Corpuscular nerve endings have small swellings at the end and include the Pacinian corpuscles, Meisner corpuscles, Merkle disks and Ruffini endings, all of which are generally responsive to touch, pressure and vibration. Non-corpuscular (free nerve) endings are bare dendrite endings and in subcutaneous fat are responsive to pain but in the epidermis they are responsive to thermal stimuli, pain, tickle and itch (Tortora and Derrickson, 2006). These two types of nerve endings can be further classified into the type of stimuli that they respond to, of which there are three major types. Firstly, mechanoreceptors respond to mechanical stimuli such as movement, stretching, pressure and deformation. Secondly, nociceptors respond to noxious stimuli, such as extreme heat or cold, strong pressure or contact with sharp objects. Thirdly, thermoreceptors respond to changes in temperature and thus are important for thermoregulation as once stimulated they relay information to the brain about the surrounding environment.

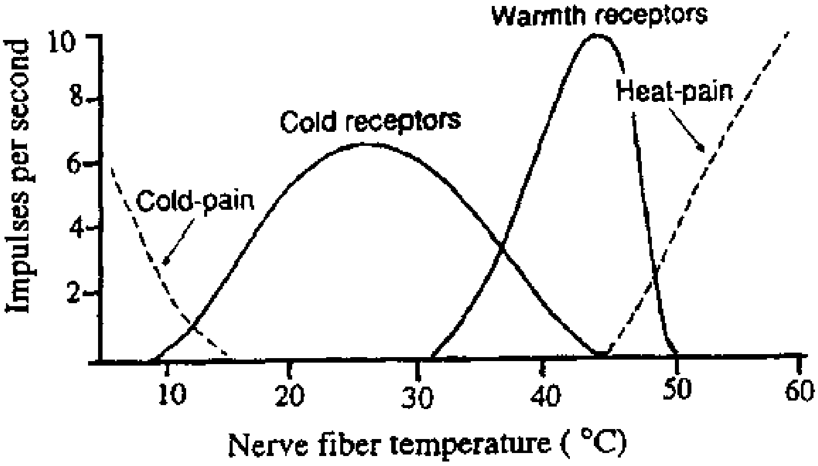


Figure 2.3: The firing frequency discharge of cold activated receptor, warmth activated receptors and nerve pain fibre at various temperatures recorded on cats (Guyton, 1991).

Thermoreceptors located on the free endings of meylinated and unmeylinated fibres are distributed at the periphery and central locations, including major organs and along the spinal cord (Bullock et al. 2001). The skin protects the body from thermal disturbances and therefore contains a large number of these receptors, of which it is suggested that there are more cold activated sensors than warm activated sensors (Hensel, 1981, cited in Parsons, 2003, p.54). The firing rates of warm and cold receptors are dependent upon the type of meylination; A delta (Aδ) fibres have thinly meylinated axons that conduct signals between 10 and 40 m·s^{-1} and are linked to cold activated fibres. Heat activated signals travel along C fibres that are unmeylinated and travel at much slower speeds (0.5-0.7 m·s^{-1}) (Hensel, 1981). Figure 2.3, illustrates the temperature range which activate cold and warm receptors recorded on cats (Guyton, 1991). Cold fibres are active between 15-38°C, and reach their peak between 23-28°C. Warm fibres are initiated around 33°C and reach their peak at ~42°C (Bullock et al. 2001). These receptors transiently increase or decrease their firing rates depending upon the direction and magnitude of the change in temperature and this ultimately influences the thermal sensation experienced (Bullock et al. 2001).

Table 2.1: Description of the transient receptor potential (TRP) family, the temperature range of stimulation and the sensation they evoke once stimulated (Ständer and Luger 2009) *indicates meylinated fibre.

Receptor	Stimulated by…	Sensation evoked
TRPV1	Noxious heat (>42°C), protons, capsaicin, anandamide,	Cold, heat, burning pain
TRPV2	Noxious heat (>52°C)	Pain induced by heat
TRPV3	Warmth (>33°C)	Warmth
TRPV4	Warmth (~25°C)	Warmth
TRMP8 (on Aδ fibre)*;	Cold (8-28°C and menthol)	Cold
TRPA1	Noxious cold (<17°C), wasabi, horseradish	Pain induced by cold burning

Recently, research had been able to distinguish the types of receptors and the range at which they are stimulated. It is the unmeylinated C fibres that are stimulated by temperature but, more specifically, it is the ion channels located at the end of unmeylinated C fibres (McKemy et al. 2002; Peier et al. 2002). These ion channels are termed the transient receptor potential (TRP) family, of which there are numerous types and are classified according to their temperature thresholds (Ständer and Luger 2009). Table 2.1 highlights the TRP family, the temperature range of stimulation and the sensation they evoke once stimulated.

The location, density and distribution of thermoreceptors play an important role in our perception of temperature. Prior to the findings of the TRP family, early research by Strughold and Porz (1931, cited in Parsons, 2003, p. 59) and Rein (1935, cited in Parsons, 2003, p.59) attempted to locate warm and cold spots across the skin which can be viewed in Table 2.2. The variation if thermoreceptors across the body and the unequal number of warm and cold receptors help explain why regional differences in thermal sensation occur.

Table 2.2: Location of cold and warm spots (per cm^2) on the human skin. *Strughold and Porz (1931) †Rein (1935) (both cited in cited in Parsons, 2003, p. 59).

Location	Cold Spots* (per cm^2)	Warm Spots† (per cm^2)
Forehead	5.5-8.0	
Nose	8.0	1.0
Lips	16.0-19.0	
Other parts of face	8.5-9.0	1.7
Chest	9.0-10.2	0.3
Abdomen	8.0-12.5	
Back	7.8	
Upper arm	5.0-6.5	
Forearm	6.0-7.5	0.3-0.4
Back of hand	7.4	0.5
Palm of hand	1.0-5.0	
Finger dorsal	7.0-9.0	1.7
Finger volar	2.0-4.0	1.6
Thigh	4.5-5.2	
Calf	4.3-5.7	
Back of foot	5.6	
Sole of foot	3.4	

2.5.3 Thermal sensation

Thermoreceptors transiently increase or decrease their firing rates depending upon the direction and magnitude of the change in temperature and this ultimately influences the thermal sensation experienced (Bullock et al. 2001). According to Hensel (1981, cited in Li, 2001, p. 55) the perception of temperature is predominately influenced by cutaneous thermoreceptors. Gagge et al. (1969b) highlighted the relationship between increasing/decreasing T_{sk} and subsequent changes in thermal sensations (Figure 2.4). As skin is in direct contact with the environment (unless covered by clothing) it is not surprising that thermal sensation is strongly correlated with ambient temperatures (Figure 2.5).

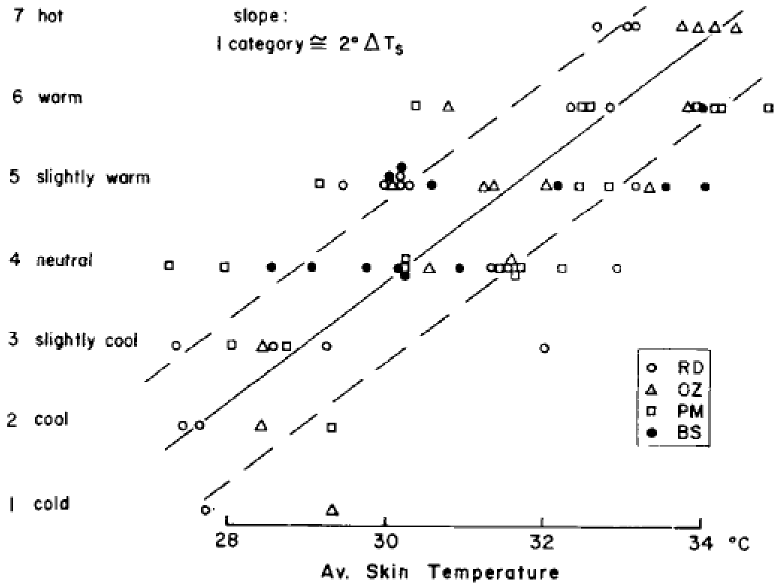


Figure 2.4: Relationship between temperature sensation and the average skin temperature after 30-40 minutes of exercises in four participants. (Gagge et al. 1969b).

During the 1830-1850's, Weber completed a considerable amount of research regarding tactile sensations (Ross and Murray 1996). With regards to the perception of temperature he determined that human perception to heat is influenced by the surface area exposed to the thermal stimulus. For example, submerging a whole hand into a flask of water and a finger tip in another (of the same temperature), the water would feel warmer when it surrounds the whole hand (Ross and Murray, 1996). To add to this he also stated that this would be the initial response, but if left for a longer duration the perception of temperature would change and become more accurate. This is often referred to as an overshoot response, whereby temperature sensations show a tendency to anticipate or initially exceed their final stages, which is common in transient environments (Arens et al. 2006). In transient conditions the response of thermoreceptors is illustrated in Figure 2.6. The graphs suggests that any temperature change causes the firing rate of the receptors to overshoot, sending strong signals to the brain, which may explain why humans are more sensitive to large step changes as opposed to slow continual changes in temperature (Hensel, 1981, cited in Li, 2001, p.41). In support of this, Hensel (1950, cited in Parsons, 2003, p.54) suggested that when the skin is exposed to changing temperatures the difference between neutral and the temperature at which hot or cold occurs (i.e. thermal threshold), decreases inversely with the rate at which temperature changed. It is evident then that thermal sensation is rate dependent and also dependent upon initial temperature.

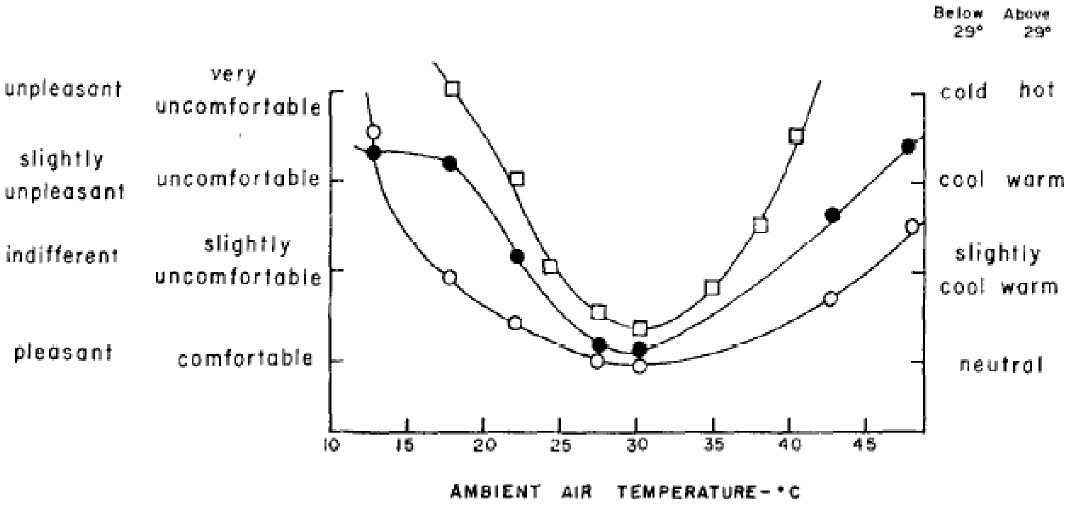


Figure 2.5: Relationship between temperature sensations and ambient temperature after 30-40 minutes of exercise (n=3) Also plotted are the pleasant votes observed by Winslow et al. (1937). (Gagge et al. 1967).

Due to the regional distribution of thermoreceptors, researchers have investigated regional sensitivity to thermal stimuli (Stevens et al. 1974; Nakamura et al. 2008, et al. 2005a;b). Different methodologies have been employed to investigate regional thermal sensitivity which can produce confounding results if the techniques used are not fully understood. The 'methods of limits' (or 'thresholds detection') requires participants to respond to a stimulus once they feel a temperature change. An alternative technique is 'magnitude estimation' whereby a participant reports the degree of sensation experienced for a given temperature. These methods produce different findings as one location may be sensitive to small temperature changes, but the degree of sensation it experiences for a given stimulus temperature may be lower than other locations. Both techniques can determine the sensitivity across regions, but the type of sensitivity is different so it is important for researchers to define and differentiate between the methods used.

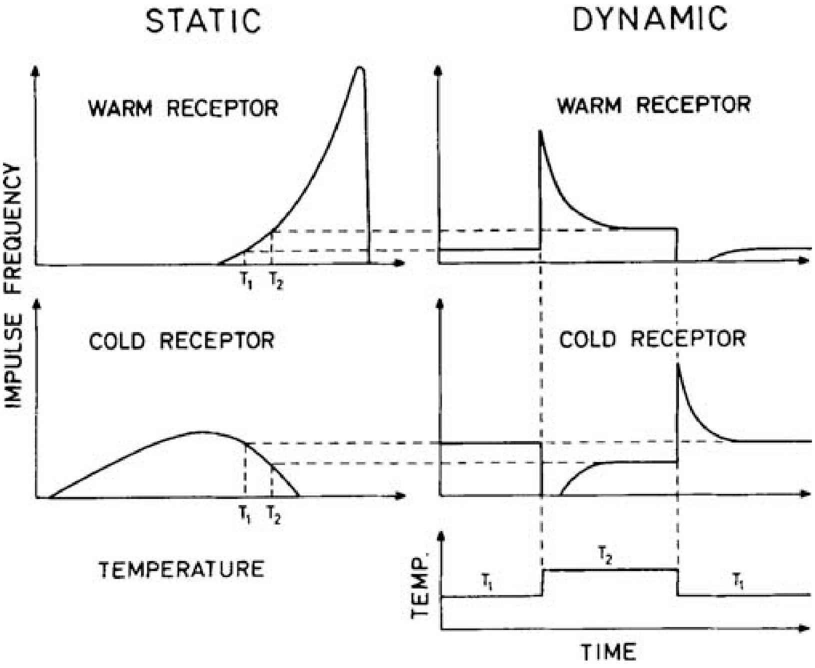


Figure 2.6: The static and dynamic properties of warm (top) and cold (middle) receptors to constant and changing temperatures. The bottom graph (right) illustrates the transient temperatures to which the receptors respond (steady temperature (T1) then an increase then a decrease back to T1). Hensel, 1981, cited in Li, 2001, p.41).

Using magnitude estimation, Stevens et al. (1974) applied a warm stimulus (thermal irradiance) on up to 10 body regions on 18 male participants in a neutral room (21°C, 50% RH) while sitting. The stimulus was applied at different strengths and also on different surface areas (3.7–22cm^2) while participants rated the sensation experienced for a given stimulus. They found the larger the area for a given stimulation the greater the estimation of warmth. This condition refers to the spatial summation of warmth, in that the sensation is relative to the surface area stimulated. For a given surface area and a given stimulus they were also able to determine regional differences in the following order of high to low sensitivity: forehead, cheek, chest, abdomen, shoulder, back, forearm, upper arm, thigh and calf. As stated earlier, the initial skin temperature will influence the sensation evoked and the work by Stevens et al. (1974) is criticised for not taken this into account.

Zhang et al. (2004) carried out extensive research in this area in an attempt to link thermal sensation and thermal comfort. They formulated a model to predict local thermal sensations and local thermal comfort on different body parts and the influence of the combinations of local sensations and comfort. They found that in environments whereby conditions are asymmetrical, thermal sensation and thermal comfort are dependent upon the sensation and comfort of local body parts and not just the whole body. The model predicts that local comfort is a function of both local and overall thermal sensations. As overall thermal sensation gets cooler a warmer local sensation causes an increase in local and overall comfort (and vice-versa). They observed the following:

1) As local sensation moves from neutral to very hot/cold, local comfort moves towards very uncomfortable.
2) Maximum comfort is a function of overall sensation; the warmer/cooler the overall sensation the greater the comfort in response to local cooling/heating.
3) Some body parts differ in their warm and cold thermal sensitivity.

In a final part of their report they assigned different weighing factors to 19 body segments for warm and cool sensations; the higher the weighing factor the more dominant the influence on overall sensation. The three most dominant locations include the back, chest and pelvis and the magnitude in thermal sensation difference (local-overall) has a strong impact on overall thermal sensation. These models aimed to correlate thermal sensation with T_{sk} and T_c and not environmental conditions. This data is useful when testing garments on thermal manikins, to predict local and whole body thermal sensations and comfort. However the data was created and validated on sedentary participants.

During exercise the thermal state of the body differs to that at rest. Applying a hot or cold stimulus to an individual with either a high or low T_c will result in a different sensation. This response is defined by Cabanac (1969) as thermal alliesthesia; a hedonistic sensation (i.e. pleasure/displeasure) aroused by a given peripheral thermal stimulus is dependent upon the internal state of the subject. According to Mower (1976) thermal alliesthesia is only applicable to thermal pleasure and not the magnitude of the thermal sensation (i.e. how hot/cold). His study was conducted on inactive participants and changes to the internal state of the body were caused by external heat loads via immersion in a water bath. Ouzzahra et al. (2012) recently re-addressed this concept to question whether the changes in magnitude sensation can result from changes in core temperature via exercise. Using the magnitude estimation, Ouzzahra et al. (2012) assessed regional distribution of thermal sensitivity to cold during rest and exercise. Their methods involved the application of a cold stimulus (25cm^2 thermal probe) on 16 body locations during rest and exercise. They found a reduction in thermal sensation to a cold stimulus and claimed that the reduction was a result of exercise induced analgesia (EIA). EIA is associated with the activation of the endogenous opioid system during exercise in which various peptides are released that has a similar effect to that of morphine (i.e. they cause a reduction in pain sensitivity) (Beaumont and Hughes, 1979). The differences in thermal sensitivity during rest and exercise are particularly important for sports' clothing manufacturers and gaps in the literature are present when considering this effect. Knowledge of the influence of a warm stimulus on regional sensitivity during exercise is required.

2.5.4 Thermal comfort

Unlike thermal sensation which can be related to thermoreceptors, there are no identifiable sense organs for thermal comfort. However, it is a recognisable feeling based upon a subjective response but is open to interpretation (Gagge et al. (1967). It has been defined as 'a condition of the mind, which expresses satisfaction with the thermal environment' (ISO 7730, 1995). However, issues arise over this definition depending on the meaning of the term 'satisfaction'. Satisfaction is associated with a positive feeling, which in this definition is associated with comfort. The opposite of satisfaction is dissatisfaction, which has a negative connotation and dissatisfaction could be caused by unwanted cooling or heating. Satisfaction would typically occur in transient conditions, such as when a cold person moves to a warm room (Parsons, 2003). The definition provided by ASHRAE (1966) suggests that comfort is always associated with a positive feeling, but it has been argued that comfort is associated with a neutral feeling, or in some cases, no feeling at all (Branton, 1969). In this case, the definition provided by Hertzberg (1972, (cited in Tan et al. 2008, p.1) is more appropriate; 'comfort is the absence of discomfort'. Although this definition was not based on *thermal* comfort, it is still viable, particularly in thermally stable conditions where neutral feelings (neither positive nor negative) can occur.

Hensel (1981, cited in Li, 2001, p.55) claimed that thermal comfort is based on an integration of afferent signals from peripheral and central thermoreceptors. Earlier research by Boje et al. (1948, cited in Chatonnet and Cabanac, 1965, p. 184) found discrepancy between comfort and T_{sk}, indicating that they were independent. However, later research by Winslow and Herrington (1949) claimed that thermal comfort was related to T_{sk} and values below 29°C and above 35°C were related to disagreeable sensations. This was later expanded by Hardy (1954, cited in Chatonnet and Cabanac, 1965, p.183) who claimed that a T_{sk} of 33°C corresponded to a comfort sensation. Any deviations away from this resulted in uncomfortable sensations but movement back towards 33°C resulted in comfortable sensations. As illustrated in Figure 2.3, it can be seen that this value corresponds with the firing rate of both warm and cold receptors. In 1963, Benzinger distinguished differences between warm and cold discomfort. By submerging participants into a bath of 38.5°C to eliminate any variations in T_{sk} people became more uncomfortable as T_c rose. When submerged into a bath of progressively lowering temperature and therefore lower T_{sk}, cold discomfort was reported despite unaltered T_c. As a result of these findings, Benzinger put forward the theory that warm discomfort was a function of rising T_c and cold discomfort was a function of lowering T_{sk}. Research by Gagge et al. (1967) supports some of these findings in an investigation that highlighted the difference between thermal sensation and comfort to warm and cold exposure of nude participants (see Figure 2.7). A reduction in T_{sk} (<33°C) caused a rapid response in temperature sensation but comfort sensations changed progressively slower. In the case of an increase in T_{sk} (>33°C) there is a rapid increase in sensation but it gradually levels off (around 'warm' sensation). This is attributed to the onset of sweating, which maintains T_{sk} at a favourable level and hence thermal sensation does not rise (McIntyre, 1980). However, the same response was not observed with thermal discomfort as it continually increased towards discomfort despite relatively stable T_{sk} and sensations (McIntyre, 1980). Gagge et al. (1967) found that thermal discomfort to warm conditions was better correlated to the amount of moisture present on the skin surface (skin wettedness).

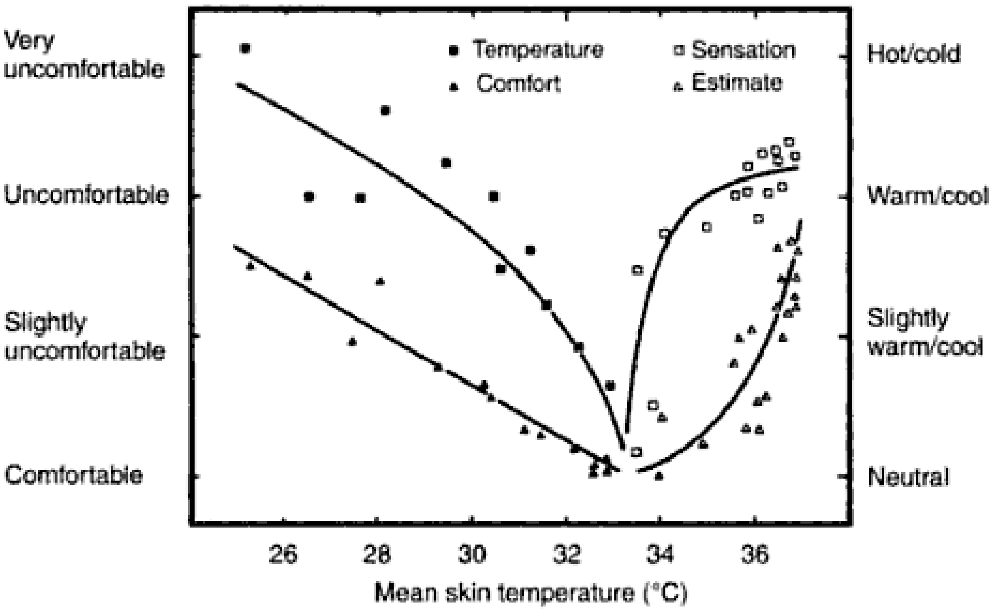


Figure 2.7: Thermal comfort and thermal sensation votes as a function of mean skin temperature. (Gagge et al. 1967, adapted version from Parsons, 2003, p. 212).

2.5.4.1 Skin wettedness

Skin wettedness was first introduced by Gagge in 1937 and refers to the extent of moisture present on the skin surface and is a ratio between actual sweat evaporation and the maximal evaporation possible in the current climate (Havenith et al. 2002):

$$w = \frac{E_{vap}}{E_{max}}$$

Where;

w = skin wettedness (nd)

E_{vap} = actual evaporation ($W \cdot m^2$)

E_{max} = maximal evaporation ($W \cdot m^2$)

Skin wettedness can be determined by the gradient between the vapour pressure of sweat on the skin surface and the vapour pressure of the environment:

$$w = \frac{E_{vap}}{E_{max}} = \frac{C_{sk} - C_e}{C_{sk}, s - C_e}$$

Where;

Csk	water vapour pressure of the skin (Pa)
Ce	water vapour pressure of the environment (Pa)
Csk,s	saturated water vapour concentration of the skin (Pa)

Skin wettedness is usually expressed as a decimal fraction, with 1.00 representing the maximum value and 0.06 representing the minimal values. Figure 2.8 illustrates the range of *w* on the skin surface. There is always a natural diffusion of moisture through the skin, which is referred to as insensible perspiration; this is given a value of 0.06 (Kerslake, 1970, cited in Hardy et al. 1970, p.139). In the extreme case, a value of 1.00 is maximal *w* in which the whole body is completely covered by a layer of sweat and is also defined as the upper limit of evaporative heat loss (Nishi and Gagge, 1977). Values of 1.00 have been reported and this would occur in ambient conditions where the evaporation of sweat is inefficient and sweat drips off the body (Candas et al. 1979a,b). Such high values are difficult to attain due to variations in sweat production across the body, as a result values of 0.8-0.9 are more common with high levels of sweat production as it represents a sporadic distribution of sweat on the surface of the skin (Candas et al. 1979a).

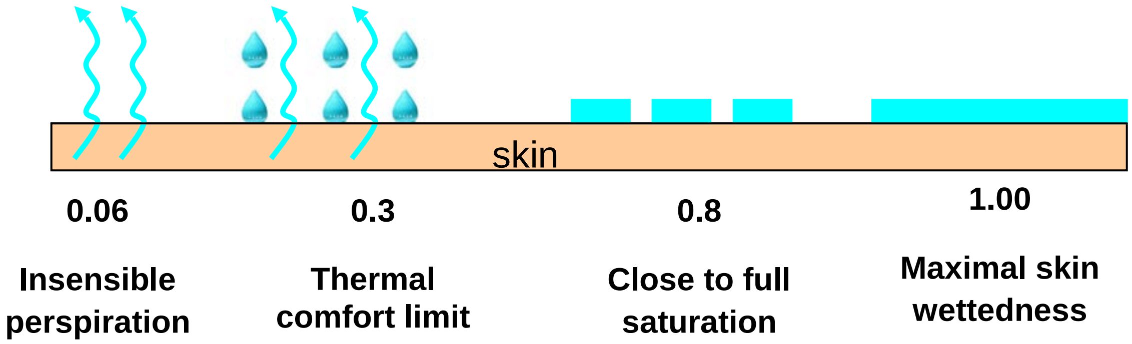


Figure 2.8: A representation of the different levels of skin wettedness on the skin surface ranging from insensible perspiration (0.06) to maximum skin wettedness (1.0).According to Gagge et al. (1969a) 0.30 is the upper limit for thermal comfort.

A reason as to why Gagge (1936, 1937) came up with a new variable associated with perspiration is due to the variability of measuring evaporation that is involved in the process of body cooling. When sweat is secreted in large amounts not all will be involved in evaporative cooling as sweat will drip off the skin or will be re-absorbed. Gagge (1937) stated that evaporation is directly proportional to the net rate of weight loss of the body (after O_2 and CO_2 corrections). However, he found errors in the direct measurements of evaporation during high sweat production as a result of sweat drippage and evaporation occurring from surfaces other than the skin (e.g. neighbouring surfaces). However, Gagge (1937) highlighted that the rate of evaporation is proportional to the difference between the vapour pressure of the skin and the vapour pressure of the surrounding air. Using this ratio Gagge formulated skin wettedness (w) which unlike evaporation (based on weight loss) remained constant during high sweat production. Under such conditions he claimed that the quantity of moisture on the skin surface will increase under such conditions, but the surface of sweat exposed to the environment remains the same.

Research conducted in hot environments and/or during exercise has reported high correlations between thermal discomfort with w (r^2=0.85, $p<0.001$) as evaporative cooling maintains thermal equilibrium (Fukazawa and Havenith, 2009; Winslow et al. 1939). Since its introduction, numerous researchers have investigated the relationship between thermal comfort and w and supported this claim (Berglund et al. 1985; Winslow et al. 1939; Gagge et al. 1969a Fukazawa and Havenith, 2009). Increase in T_c and T_{sk} causes an increase in sweat production to facilitate heat balance. This mechanism maintains T_{sk} and thermal sensations at favourable levels, yet discomfort increases. This increase in discomfort has been attributed to the amount of moisture present on the skin surface, namely skin wettedness (*w*). Gagge et al. (1969a) proposed a model to predict thermal comfort when thermal equilibrium can be maintained by sweating. They claimed that thermal comfort can be achieved when *w* is below 0.30 (Figure 2.9). The data used in Figure 2.9 came from 4 subjects during rest and exercise. Such low participant numbers are common in early literature, but still raises the question as to whether this was enough to produce any significant responses.

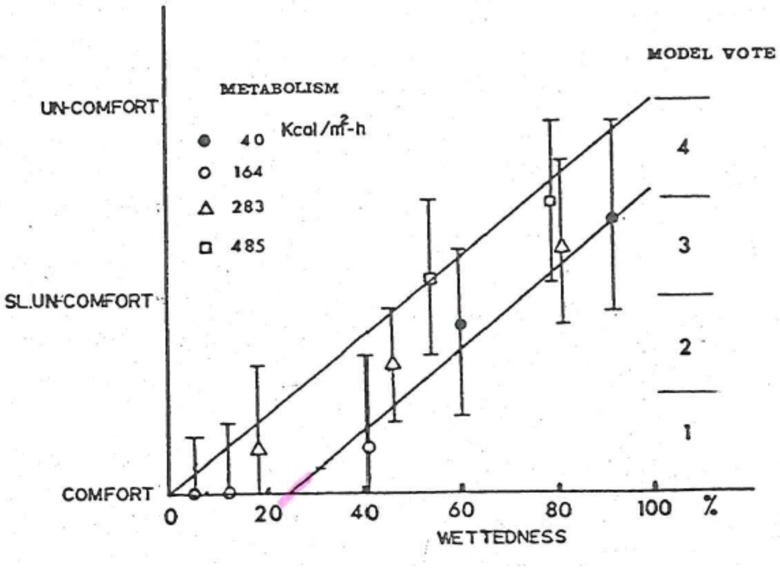


Figure 2.9: Relationship between thermal comfort and skin wettedness. The two diagonal solid lines represent a 25% range of skin wettedness for the vote observed. The four "model votes" on the right hand side represent 25% step increases in skin wettedness (Gagge et al. 1969a)

A practical viewpoint is that humans tend to accept higher levels of perspiration in certain local areas (e.g. axillary region) without it being perceived as uncomfortable, yet scientific research needs to establish the comfort limits of local body parts to *w*. Regional differences have been established in sweating but how we perceive the build up of sweat on the skin surface and the comfort limit of local areas is a relatively unexplored area. As a result of the evidence of regional variations of thermoreceptors, sweat glands, thermal and humidity sensitivities, Fukazawa and Havenith (2009) conducted an investigation into the effects of local and whole body *w* on thermal comfort (n=8). They hypothesised that comfort was not affected by whole body *w* (w_{body}) but a single zone, most likely the wettest one. In order to carry out this investigation, they increased regional skin wettedness (w_{local}) in target zones (arms, thighs, front torso, back torso) using clothing with different water vapour resistances (permeable and impermeable zones of 32 and 62 $m^2 \cdot Pa \cdot W^{-2}$, respectively). The *w* of selected target areas was increased from below the comfort level (<0.30) to above the comfort limit (>0.30), whilst all other areas were maintained below the comfort limit (<0.3). The comfort limit was identified for whole body, (0.36 ± 0.05), front torso (0.4 ± 0.11), back torso (0.45 ± 0.18) and extremities (legs and arms) (0.32 ± 0.07). Whole body thermal comfort was significantly correlated with w_{body} (r^2=0.85 p<0.001) and the comfort limit of the whole body was 0.36 which was slightly higher than that reported by Nishi and Gagge (1977) (0.30). However, they claimed that the comfort limit associated with w increases with metabolic rate. The equation below indicates the comfort limit suggested by Nishi and Gagge (1977). A result of 0.36 from Fukazawa and Havenith was in good agreement with the prediction provided by Nishi and Gagge (1977):

$$W < 0.0012 * \text{metabolic rate} + 0.15$$

$$W < 0.0012 * 174.6 + 0.15 = 0.359$$

w_{body} is consistent with previous literature, yet w_{local} is relatively new to this research area and an in-depth look into the results from this study suggests that the results are not so clear-cut. The main problem can be explained from Figure 2.10 and Figure 2.11 (taken from Fukazawa and Havenith, 2009). Figure 2.10 illustrates significant differences in w at the four target locations and Figure 2.11 indicates that the arms and thighs have a higher thermal sensitivity to w than the front and back. From Figure 2.10 a clear difference between target zones and non-target zones for the front and the back is evident, consistent with the aims of the experiment. However, the contrast is less obvious for the extremities, particularly for the arms. During test type C (arms, indicated by ■) w at the arms is only slightly higher than the front and back, hence the goal of raising w in those zones substantially above the others was not fully achieved. Alongside this, Figure 2.11 suggests that the arms are the most sensitive region. It is questionable if thermal comfort was influenced solely by the arms as the w_{local} at the front and back was only slightly lower than the arms (0.35, 0.36 and 0.41, respectively). Future tests should aim to make stronger contrasts between zones so that researchers can be certain of the sensitivity to w_{local}. It is likely, as suggested by the authors, that they were not able to make clear differences between these zones due to the much higher levels of sweat production at the torso compared to the extremities (Smith and Havenith, 2011).

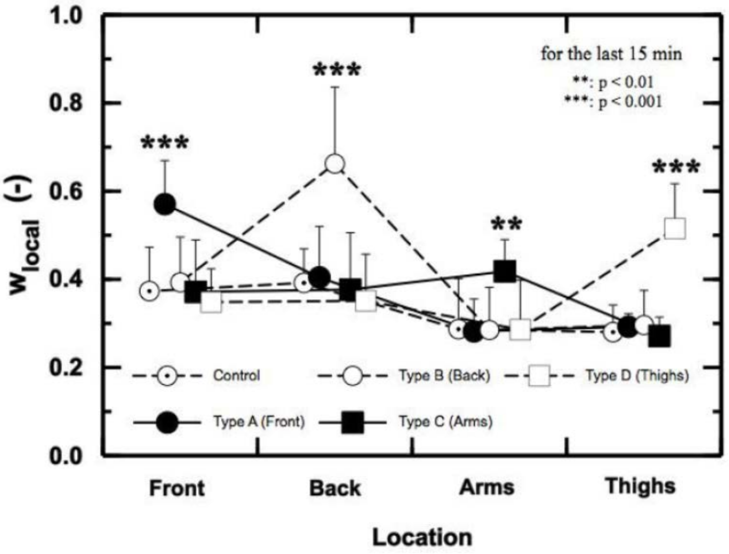


Figure 2.10: Mean skin wettedness measured at four locations whilst wearing five different types of garments. The type of garment indicates which area of the body was manipulated to increase local skin wettedness (i.e. type B (Back) (taken from Fukazawa and Havenith, 2009).

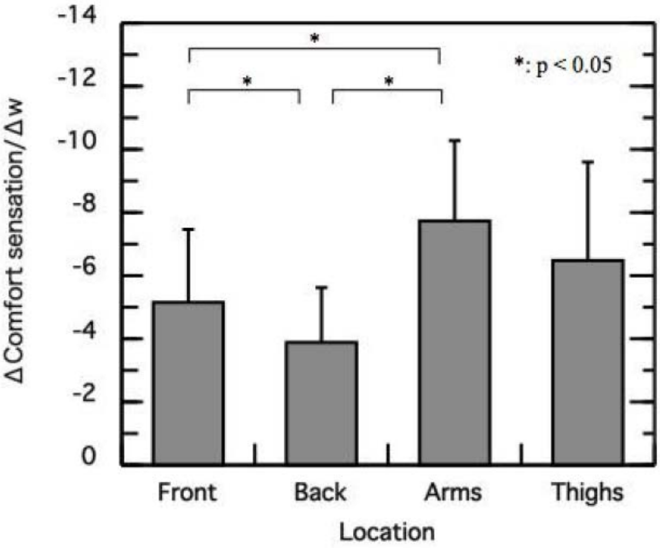


Figure 2.11: Thermal comfort sensitivities to skin wettedness in the four target areas (taken from Fukazawa and Havenith, 2009).

Umbach carried out a similar study in 1982 to Fukazawa and Havenith (2009) with some slight difference in methodology. Fukazawa and Havenith (2009) aimed to determine the limits of thermal comfort, whereas Umbach aimed to find the limits of wearer comfort and thus used different perceptual scales. Umbach's main focus was upon the influence of relative humidity (*RH)* on local sensations, but he did convert his findings into w_{local} and w_{body}. Results from this study on 4 males found subjective sensations to moisture and wear comfort were strongly related to relative humidity (r^2=0.92) or absolute water vapour partial pressure of the microclimate (r^2=0.56). As a result, Umbach concluded that the clothing's moisture transport capacity would strongly influence wear comfort. According to Umbach's results a whole body clothing comfort score can only be achieved if the relative humidity in the microclimate of a uniform clothing ensemble remains below 55% (w_{body}<0.32). This was found to be highly correlated to wear comfort (r^2=0.98). However, sports clothing designed for thermoneutral or hot environments will tend to be non-uniform (i.e. shorts, short sleeved or sleeveless t-shirts). In this situation the build up of moisture will vary in regional locations, therefore he assessed regional sensitivity to relative humidity, water vapour pressure and *w*. The results are compared with Fukazawa and Havenith (2009) in Table 2.3 and indicate consistency between their findings. Umbach found the chest and back tolerate higher levels of relative humidity than the extremities. The microclimate in the lower leg must remain below 46% (w_{local} of 0.10) to be perceived as comfortable while the chest was 75% (w_{local} of 0.42). However, it is probable that the relative humidity of the extremities will be lower than the torso due to the lower distributions of sweat rate (Smith and Havenith, 2011), so it remains questionable as to whether comfort sensation is caused by other body parts.

Table 2.3: A comparison of the local thermal comfort limits of different body sites to skin wettedness (i.e. the threshold for when each body site is considered to be uncomfortable), according to Umbach, (1982) and Fukazawa and Havenith (2009). * Fukazawa and Havenith (2009) target locations were front thigh, front torso, and back torso.

Regional zones	Umbach (1982)	Fukazawa and Havenith (2009)
Lower leg	0.10	-
Upper leg*	0.41	0.32
Arms	0.32	0.32
Chest*	0.42	0.40
Back*	0.49	0.45
Whole body	0.30	0.36

Fukazawa and Havenith (2009) only assessed four regional zones; front torso, back torso, arms and legs, yet researchers have shown large variations within these sites, particularly at the torso as shown in Figure 2.2 (Smith and Havenith, 2011, 2012; Havenith et al. 2008). The variations of sweat distribution within the torso imply that *w* will vary in the front and the back torso, which should be considered in future investigations.

Skin wettedness is a constructed physiological variable and has an upper limit of 1.0. Once a value of 1.0 is achieved, evaporation equals the maximum possible for that environment and according to Candas et al. (1980) sweat drippage occurs from values <1.0. In conditions of high sweat rates, the influence of w on thermal comfort is questionable unless maximum discomfort is reached. However, many studies assessing the relationship between thermal comfort and *w* are limited to transitions from comfort to discomfort and neglect extreme states of discomfort (Fukazawa and Havenith, 2009; Umbach, 1982). Research has found that the presence of sweat causes the epidermis to swell which makes the skin receptors more sensitive (Berglund and Cunningham, 1986; Berglund, 1995, cited in Arens and Zhang, 2006, p.595). Due to the upper limit of *w* and the influence sweat has on receptors it is interesting to understand whether the hydration within the skin influences various sensory responses, including thermal comfort. The hydration of the skin can be measured with several instruments, one of which is galvanic skin conductance (GSC). GSC is an electrodermal measurement which signifies an increase in the skins ability to conduct electricity which is improved with the presence of sweat. The next section will discuss GSC in detail.

2.5.4.2 Galvanic skin conductance

Since the 1880's, electrical measurements of the skin have been carried out with initial investigations by Féré (1888, cited in Edelberg, 1972, p.368) establishing the decrease in skin resistance due to vasodilatation, which was later associated with sweat gland secretion by Tarchanoff (1890, cited in Edelberg, 1972, p.368). Since then, electrodermal activity has been investigated and is defined as changes in electrical properties of the skin. It has been associated with the autonomic nervous system due to the activity of sweat glands in the response to emotional and thermoregulatory sweating and the effect of sweat on the conductance levels of the skin. Since its introduction, the electrical activity of the skin was mainly investigated with reference to changes in autonomic sympathetic arousal associated with anxiety, emotion and the infamous polygraph lie detector test invented by Larson, and Keeler in the early 1920's (Geddes, 2002). Despite the link between sweat gland activity and thermoregulation, the measurement of GSC has predominantly been investigated for psychophysiological research and there is currently limited research on GSC in the area of environmental physiology. The understanding of the electrical properties of the skin can be enhanced with knowledge of the structure and function of the skin and the sweat glands, which may justify the use of GSC for environmental physiological research.

Figure 2.1a illustrates the skin structure, from which three layers are distinguishable; the epidermis is the most superficial layer and has a high electrical resistance due to a thick layer of dead cells which are comprised of keratin (Edelberg, 1972). Underneath the dermis is an area known as the hypodermis or subdermis where the sweat ducts are located. Beneath this is a subcutaneous adipose layer, which contains sweat glands, hair follicles, fine muscle filaments and blood vessels (Li, 2001). Skin is a good conductor of electricity which is enhanced by the presence of a weak electrolyte solution (sweat) (0.3% NaCl salt solution). As the ducts fill with sweat, GSC increases and as sweat travels towards the surface of the skin, the hydration within the corneum increases. According to Kilgman (1964) the corneum is very hygroscopic and can hold up to 70% of its own weight in water. The increase of water within the corneum will increase the conductivity of the skin. The amplitude of the change in conductance depends on the amount of sweat delivered to the duct and on the number of sweat glands activated (Thomas and Korr, 1957; Edelberg, 1972). Edelberg (1972) provides an in-depth description of the relationship between physiological changes and electrodermal activity. In summary, Edelberg (1972) proposed a sweat circuit model which states that the skin conductance level (SCL), otherwise known as the basal measurement is usually stable when sweat glands are inactive. Filling of the sweat glands causes skin conductance to increase and as this sweat rises up the coiled portion of the duct, it further increases the conductance of the skin. When secretion stops sweat remains in the duct and GSC stabilises. Sweat will either slowly diffuse into the corneum or be reabsorbed into the sweat gland which will reduce GSC. Changes in GSC have been shown to occur even before sweat is observed on the skin surface (Darrow, 1964). As a result, the measured changes in GSC have been associated with the pre-secretory activity of the sweat glands, the filling of the sweat ducts and the hydration status of the corneum. Research has established that changes in GSC depend on how much sweat is delivered to the duct and on the number of sweat glands activated (Fowles, 1986).

Limited research using GSC as a measure of sweat gland activity for thermophysiological studies has been conducted. However, Machado-Moreira et al. (2009) investigated GSC during thermal and psychological stress tests and found an increase in change of GSC (0.50 ± 0.11 to 7.06 ± 1.04 μS) from exposure to heat alongside changes in T_c (36.37 ± 0.06 to 36.66 ± 0.07°C), $\bar{T}_b$ (35.8 ± 0.07 to 36.4 ± 0.08°C) and sweat rate (0.21 ± 0.02 to 0.66 ± 0.1 $\text{mg}\cdot\text{cm}^{-2}\cdot\text{min}^{-1}$). These changes were larger than those experienced during the psychological stress test. This coincides with data from Thomas and Korr (1957) who found that GSC correlated linearly with increasing and decreasing number of active sweat glands (r^2=0.81). Further research needs to establish this parameter for thermophysiological research, but theoretically GSC can be a reliable and informative measure. For thermal comfort studies it may produce interesting results as it has previously been stated that the epidermis swells due to the presence of sweat and this increase receptors sensitivity within the skin (Kerslake, 1972; Willis, 1985, cited in Li, 2001, p.37). If skin GSC can provide information regarding the hydration status of the epidermis then more sensitive data may be obtained regarding various types of sensations.

2.5.5 Wetness sensation

As there are no ‘wet’ receptors in the skin, the sensation of sweating or wetness is a state of feeling based upon a subjective response. Researchers have attempted to find correlations between sudomotor activity (sweat rate, *w* and skin humidity) and the sensation of sweating or wetness (Nielsen and Endrusick, 1990; Gwosdow et al. 1989). Due to the absence of wet receptors (Nielsen and Endrusick, 1990), it is likely that the sensation of wetness is due to sweat moving along the surface of the skin; this stimulates tactile receptors and provides feedback of the presence of sweat. The cooling mechanism of evaporation is also associated with the sensation wetness due to the temperature drop caused by evaporative cooling (Wang et al. 2002). Regardless of this information, researchers have attempted to quantify subjective responses of wetness to different measurements of sudomotor activity.

Toftum et al. (1998) investigated subjective responses to 5 different levels of skin *RH* (32-75%), otherwise defined as a *w* value ranging from 0.09-0.48 during sedentary activity. Skin *RH* was correlated with perception of skin humidity (r^2=0.65) and perception of clothing humidity against the skin (r^2=0.92). This response was the same between males and females despite the fact that the females had lower skin *RH*. This infers that the sensations experienced are relative to individual skin *RH*. They found that the upper back and axilla had the highest level of humidity sensations. Unfortunately no data was available for these body sites to see whether this corresponded to higher levels of skin *RH* or to quantify it. They did find that subjective perceptions of skin humidity at the chest had the highest impact on perceived overall acceptability of skin humidity. Nielsen and Endrusick (1990) found moderate correlations between whole body sensation of skin wetness and *w* (r^2=0.40) during two

40 minute cycle bouts interspersed with a 20 minute rest period at 5°C, 54% RH. They also found moderate correlations between the sensation of wetness of the clothing and *w* (r^2=0.39).

Sweat evaporation cools the underlying skin, which has been put forward as a theory for the perception of moisture. Newton et al. (2007) modified microclimate *RH* whilst maintaining a stable temperature around the torso and measured the perception of skin wettedness. An increase in microclimate *RH* did not cause an alteration in skin wettedness perception but did cause an increase in local T_{sk} which strongly influenced thermal sensation. This was associated with the reduction in heat loss due to the elevations in *RH.* The influence of change in microclimate *RH* on thermal sensation was supported by a later study from the same authors (Newton et al., 2009), who found strong relationship between the perception of microclimate RH and skin temperature change. This supports other authors who suggest the perception of wetness is the effect of evaporative cooling of sweat from the skin surface (Lee et al. 2011; Tiest et al. 2002; Li, 2005). Bentley (1990) reported that cold temperature induced by a tight fitting garment (of even pressure) stimulated the feeling of wetness in the absence of moisture. The mechanism of evaporative heat loss has frequently been identified as a cause of wetness sensation due to the cooling of local T_{sk}. This has also been supported by Plante et al. (1995) who noted that participants sensed the skin as being 'damper' with larger drops in T_{sk}. However, exposure to hot conditions or with exercise causes an increase in T_{sk}, skin *RH* (as a result of an increase in sweat rate) and the sensation of wetness as found by Toftum et al. (1998).

Overall, the studies in this area support the notion that factors influencing the sensations of wet skin are related to both a temperature change at the skin, (whether induced by sweat on the skin or by moisture in the clothing) and tactile properties. Some inconsistency exist which is due to a lack of consensus in the perception measured and the scales used. Perception of dampness, perception of humidity, sensation of wetness, sensation of sweating either in the skin or clothing have all been investigated. Alongside this, much of the research aimed to find correlations with physiological parameters but failed to quantify it. Many of the studies in this area assess the perception of wetness/sweating/moisture via changes in the microclimate. Newton et al. (2007, 2009) artificially changed the microclimate *RH* via small vessels or using air perfused vests placed over target areas. However, the mechanisms behind the perception of sweating/wet skin may not only be affected by the *RH*, but may also be related to production of sweat from within the skin as it has been suggested that sweating causes swelling of the epidermis which in turn increases receptor sensitivity (Berglund and Cunningham, 1986; Berglund, 1995, cited in Arens and Zhang, 2006, p.595). It is debatable whether perceptual responses associated with sweating can be replicated by changing the microclimate.

2.6 Measurement scales

Psychometric scales assess ones attitudes/feelings/beliefs towards a statement or question. Rensis Likert (1932, cited in Albaum, 1997) developed a framework for which psychological attitudes could be measured on a scale in a scientific manner. A Likert scale consists of the following features:

- a scale containing several items;
- response levels with consecutive integers;
- response levels defined with labels arranged more-or-less on evenly spaced gradations;
- response levels are bivalent and symmetrical about a neutral middle, therefore containing an odd number of responses.

These types of scales are also referred to as categorical scales which assign a number to a characteristic. Scales can be either unipolar or bipolar but Parsons (2003) argued that thermal sensation is bipolar, ranging from very hot to very cold with neutral mid-range. However, it is also possible to just assess one thermal sensation (i.e. cold or hot), in which case unipolar scales are used. Frequently, bipolar scales are used for the assessment of thermal comfort and wetness sensation but the definitions of the terms ‘very comfortable’ and ‘very dry’ are questionable. Bipolar scales for the assessment of comfort should be limited to transient conditions where changes in temperature can produce positive feelings in situations of extreme conditions or allesthesia. Leon et al. (2008) argued the advantages of using unipolar scales as they focus upon a single subjective response, and the magnitude of the feelings experienced can be investigated more thoroughly (e.g. how hot). Obviously this is only applicable if you predict the participant will only experience one side of the response (i.e. only neutral-cold or neutral-hot). Scales for the assessment of skin wetness/sweating sensation should be limited to unipolar scales use due to the uncertainty of the definition of very dry skin with regards to sweating. This will be discussed in more detail below.

Subjective responses to thermal environments may be used independently or to compliment objective measures (e.g. comfort equations) or physiological responses (Nicol et al. 1995). According to Parsons (2003) many studies use a 7-point scale to measure thermal comfort and sensations but fail to explain why a person perceives the environment in such a way. Undoubtedly there are problems with subjective responses due to variations in definitions of thermal comfort and previous experience; as a result numerous scales have been designed to strengthen the reliability and validity of such scales. Nicol et al. (1995) divided subjective scales into 5 categories:

1. perceptual
2. affective
3. thermal preference
4. personal acceptance
5. personal tolerance

Perceptual responses refer to how an individual may feel at a given moment in time (e.g. cold/hot?); affective response refers to how they find the environment (e.g. comfortable?); thermal preference questions how they would like to feel (e.g. warmer/cooler?); personal acceptance questions how acceptable/unacceptable the environment is and finally, tolerance questions how tolerably they find the environment. Parsons (2003) presents subjective questionnaires utilised to assess thermal comfort. These extensive questionnaires cover the perceptual and preference responses and seek information about their general feeling, which is useful when assessment over long periods of time is not possible (Parsons, 2003). These methods of assessment are useful when the participant is stationary or has sufficient time to comprehend and complete the questions, yet during exercise the completion of these forms is difficult, if not almost impossible. A more simple method of assessing thermal comfort (but at the risk of less information) are two common scales that have been used by researchers; the Bedford comfort scale (1936) and the ASHRAE sensation scale (1997).

The Bedford scale has been criticised as it contains sensations of both warmth and comfort, yet this ‘affective’ scale does allow comparisons of how the participants would like to feel (Parson, 2003; McIntyre, 1980). The ASHRAE scale originally had ‘comfortable’ as the mid-point, which suggests the absence of discomfort, but this was later replaced with ‘neutral’ as it is possible to feel thermally neutral yet uncomfortable due to non-uniformity (McNall, 1967). Research by Griffiths and Boyce (1971) found that the Bedford scale and ASHRAE scale were closely related to air temperature (r^2=

0.62-0.71 and r^2=0.67-0.76, respectively). The validity of the ASHRAE sensation scale has been well established and is widely used (ASHRAE, 1997). Givoni (1976) expanded the ASHRAE sensation scale by adding ‘very hot/cold’ and ‘unbearably hot/cold’ at either end of the scale. The purpose of this was to allow assessment in extreme environments and it can also be argued that this prevents a ‘ceiling effect’ when rating thermal sensations. Scales have also been altered slightly and numbers have been inserted between each category vote to increase the sensitivity of the scale.

Table 2.4: The Bedford comfort scale (Bedford, 1936) and the ASHRAE sensation scale (ASHRAE, 1997). *originally read ‘comfortable’.

Bedford comfort scale		ASHRAE sensation scale	
Much too warm	7	Hot	7
Too warm	6	Warm	6
Comfortably warm	5	Slightly warm	5
Comfortable	4	Neutral*	4
Comfortably cool	3	Slightly cool	3
Too cool	2	Cool	2
Much too cool	1	Cold	1

Common comfort scales range from ‘very comfortable’ to ‘very uncomfortable’ (Fukazawa and Havenith, 2009; Arens et al. 2005a;b). However, it can be argued what is meant by being ‘very comfortable’, especially if comfort is considered to be the absence of discomfort. When in a comfortably neutral condition, humans are less aware of their thermal environment and often experience no discomfort (Kuno, 1995). In this case comfort scales should range from ‘comfortable’ to ‘very uncomfortable’ and by numbering the uncomfortable categories as ‘minus’ values should emphasise the fact that a sensation other than comfortable are undesirable/ unpleasant sensations. Situations whereby someone might feel ‘very comfortable’ are during transient conditions or when a stimulus helps return T_c and/or T_{sk} to neutral. Zhang et al. (2004) demonstrated the usefulness of such a scale in non-uniform and transient environments as participants scores ranged from ‘very comfortable’ to ‘very uncomfortable’ when the thermal environment caused warm or cold pleasant sensation depending on the previous condition. Therefore, when assessing comfort in transient conditions a scale ranging from ‘very comfortable to very uncomfortable’ seems plausible, yet in stable conditions a scale ranging from ‘comfortable-very uncomfortable’ would be better suited. An alternative approach is to use a bipolar ‘comfort scale’, but collapse the comfort side before analysis.

Another method of assessing thermal comfort and sensation is the use of visual analogue scales (VAS), which was initially introduced by Hoffman and Pozos (1989). VAS involves presenting the participant a straight line (no numbers) with labels at either end. Participants are asked to rate a construct (sensation, comfort, regional sensations etc) by marking a point along the line which reflects their current status (Leon et al. 2008). VAS can be used as either unipolar (i.e. ‘neutral’ to ‘extremely cold’) or bipolar (e.g. ‘hot’ to ‘cold’). Scores are obtained by applying a template with measured intervals marked (e.g. 0-10 or 0-100) along the scale, according to Leon et al. (2008) this makes the scale sensitive to small changes and is particularly useful in dynamic environments. Leon et al. (2008) also argue that VAS have a greater accuracy for detecting humans perceptions as the participant is not forced to make ratings according to numbers or restricted to verbal categories which may not reflect their true current status. Davey et al. (2007) compared VAS with ASHRAE Likert scale in stable and dynamic thermal environments and their evidence supports the notion that VAS has greater reproducibility and reflects body temperature more-so than Likert scales. As pointed out by Lee et al. (2009), VAS is more popular with psychological research whereas categorical scales are more widely used in thermal physiological and ergonomic research. New research into the reliability and validity of VAS in this research area is arising, but more conditions and environmental scenarios are required to validate the use of VAS scales before they become the ‘norm’ of assessing subjective responses.

The sensation of moisture has previously been assessed using a VAS by Wong et al. (2005) with the words ranging from very clammy to very dry. Plante et al. (1995) used a combined VAS and categorical scales using intermediary words including definitely dry, barely dry, slightly damp, moderately damp and very damp. Ha et al. (1995) used scales similar to the ASHRAE and Bedford bipolar scales to measure humidity sensations using ‘too wet, wet, slightly wet, neutral slightly dry, dry and too dry’ (translated to Japanese). There is less clarity over the wording of the scales required to assess the feeling of wet skin or sweating sensation. Words range from various degrees of dryness to the feelings of dampness, clamminess, wetness and the degree of sweating. As stated earlier the assessment of wetness/humidity should be done so using unipolar scales as the definition of ‘definitely dry/very dry’ comes under scrutiny when referring to the concept of sweating. ‘Very dry’ skin is associated with medical conditions such as eczema or other related skin conditions. Clearly the choice of words should aim to address the research question, but careful consideration of the words meaning is essential. Humidity contains connotations of both warmth and wetness or when referring to weather: warmth and dampness. This may be more appropriate for assessing humidity of clothing as opposed to skin humidity. Confusion may exist between the words ‘damp’ and ‘clammy’, particularly for those participants whose first language is not English. As the sensations are subjective and large variations can exist between and within participants it is essential to have clarity with all aspects of the scales used.

2.6.1 Analysis of Subjective scales

The scales to be used in this thesis are presented in Table 2.4 and will be the point of discussion for this section. Whether many subjective scales can be considered as interval or ordinal data is a subject of disagreement amongst psychophysiologists. The foundation of the arguments lies primarily with the scale being arbitrary as no value is assigned to the scales other than what the researcher assigns to them. However, Likert scales generally have a progressive integer value and the scales in Table 2.4 show an order of magnitude that can be conceptually understood. The main argument for treating Likert scales as interval data is whether the distance between each successive point is equidistant. Therefore perceptual scales tend to include a middle category and the levels surrounding this are symmetrical, as with the thermal sensation scale in Table 2.4. Researchers have adopted this approach for wetness sensation scales and thermal comfort scales without considering the meaning of ‘very dry’ or ‘very comfortable’. However, the latter is a common occurrence in transient conditions. Traditionally, perceptual scales are inferred as being interval data and very few researchers have considered any problem with this assumption. Stevens and colleagues conducted many experiments investigating the magnitude of perception in relation to a physical stimulus. A key part of the research established that the ratios in a stimulus value produced equal ratios in perceptual magnitude. Stevens (1966) argued that every sensory continuum exhibits the same invariance; an equal stimulus ratio produces an equal sensation ratio. Since then, researchers have investigated this theory on various types of stimuli, including Refinetti (1989), who found a strong linear relationship between sensory magnitude and stimulus magnitude (r^2=0.98). McIntyre (1978) also found that the degrees between each point of the ASHRAE sensation scale (excluding the extreme values) are psychologically located at equivalent distances. Since then, thermal perceptual responses have mostly been treated as interval data and analysed using parametric tests without question. Although it cannot be denied that a Likert scale is ordinal, if it is symmetrical and equidistant then it behaves more like an interval-level measurement. This is beneficial as, if it was treated just as an ordinal scale, then some valuable information could be lost if the ‘distance’ between Likert items were not available for consideration. The ASHRAE sensation scale has been studied and accepted as an interval scale, yet wetness sensation and thermal comfort has not. Based on the reasoning presented by Stevens and colleagues and the linear relationships found between thermal sensation, thermal comfort and wetness sensation in pilot studies these scales too will be treated as interval data. This is supported by carefully constructing the scales to increase in order of magnitude and carefully word each level as increasing beyond its predecessor, which is discussed below.

Table 2.5: Subjective scales for the assessment of thermal sensation, wetness sensation and thermal comfort to be used in this thesis.

Thermal sensation	**Wetness sensation**	**Thermal comfort**
+10 Extremely hot	0 Dry	0 Comfortable
+9	1	-1
+8 Very hot	2 Moist	-2 Slightly uncomfortable
+7	3	-3
+6 Hot	4 Wet	-4 Uncomfortable
+5	5	-5
+4 Warm	6 Dripping wet	-6 Very uncomfortable
+3		
+2 Slightly Warm		
+1		
0 Neutral		
-1		
-2 Slightly cool		
-3		
-4 Cool		
-5		
-6 Cold		
-7		
-8 Very cold		
-9		
-10 Extremely cold		

A modified ASHRAE thermal sensation scale was opted for, which ranges from extremely hot to extremely cold with neutral in the middle. A bipolar scale was opted for as it is possible that the participants may experience some degree of cold during the resting phase despite the main trials being in hot conditions. The scale was modified from the original ASHRAE scale with the addition of extremely hot and extremely cold to prevent a ceiling effect, alongside numbers in between each sensation to increase the sensitivity of the scales. Although it has been suggested that a 7-point scale is within a humans span of judgement (McIntyre, 1980; Miller, 1956) the experiments employed in this study include exposure to heat whilst undertaking exercise and therefore stronger thermal sensations are likely to be experienced. Thermal comfort and the wetness sensation scale are limited to 7 points and are unipolar. A modified Griffiths and Boyce (1971) scale for thermal comfort was used with numbers in between the descriptors as done with thermal sensation. As uniform conditions will be used throughout this thesis a bipolar scale was deemed unsatisfactory based on the definition that comfort is the absence of discomfort. For wetness sensation, a scale based on Ha et al. (1995) was used which was modified so to be only unipolar as the terms beyond dry such as 'very dry' are illogical. As with thermal comfort and thermal sensation it has numbers between each descriptor to increase the sensitivity.

Despite recent research stating that VAS have a greater accuracy for detecting human perceptions (Davey et al. 2007; Leon et al. 2008) they will not be used in the present thesis. As stated by Lee et al. (2009) VAS are more popular with psychological research whereas categorical scales are more widely used in thermal physiological and ergonomic based research. In order to compare with other research in this field, categorical scales will be used. Additionally, some studies carried out in this thesis are concerned with the transition away from 'comfortable' and 'dry' and a corresponding physiological variable (e.g. w, GSC, T_{sk}). In order to determine the transition away from comfortable a 'threshold' on the sensation scale must be defined. This is easily defined on the categorical scales in Table 2.4; whereas an assumption as to when they have crossed that threshold would be required on a VAS. The validity of this 'threshold' on the VAS comes under question.

2.7 Summary of literature review

The review has highlighted the complexity of physiological factors that influence thermal perceptual responses and some gaps in the literature exist. In the design of sports clothing, manufactures must consider the interaction of the wearer with the physical environment and the physiological response that will result from exercise. Thermal comfort, wetness sensation and thermal and sensation are three important perceptual responses that clothing manufactures should consider. From the review of the literature on these perceptual responses the following conclusions are drawn:

2.7.1 Thermal comfort

Thermal comfort in warm conditions has been attributed to the amount of moisture present on the skin surface, otherwise known as skin wettedness. A w_{body} value of 0.30 is prescribed as the comfort limit at rest (Gagge et al. 1969a). However regional differences in sweat rate have been reported in the literature (Smith and Havenith, 2011, 2012) and regional differences in thermal comfort to w have recently been investigated (Fukazawa and Havenith, 2009). However, methodological issues mean that the findings were not totally conclusive and further research needs to confirm the local thermal comfort limits across the body. Additionally, much of the research concerning thermal comfort and skin wettedness is primarily focused upon the transfer from comfort to an uncomfortable. During exercise and with exposure to the heat sweat rates increases and the relationship between thermal comfort and w has not been investigated. In such cases it is predicted that w will reach its maximum value (1.0) whilst discomfort continues to increase. Research has reported that as sweat rate increases the epidermis swells which makes the skin receptors more sensitive (Berglund and Cunningham, 1986). Therefore, galvanic skin conductance (GSC) which has been associated with the pre-secretory activity of the sweat glands, the filling of the sweat ducts and the hydration status of the corneum may be a better predictor of thermal comfort. Theoretically GSC is a good indicator of sudomotor activity but measurements have predominantly been conducted for psychophysiological research at low sweat rates and there is currently limited research in the area of environmental physiology with its often high sweat rates.

2.7.2 Wetness sensation

Due to the absence of wet receptors (Nielsen and Endrusick, 1990), it has been suggested that the sensation of sweating or wetness is a result of tactile stimulation as sweat moves across the skin surface. The cooling mechanism of evaporation is also associated with the sensation of sweating and/or wetness due to the temperature change with evaporative cooling. However, exercise or exposure to hot conditions may result in a simultaneous increase in skin temperature and sweat rate; raising questions as to what would stimulate the perception of wetness. Research that has considered the influence of w or microclimate relative humidity has found moderate to strong correlations with physiological parameters but failed to quantify it.

2.7.3 Thermal sensation

Of all the three perceptual responses reviewed in the literature, thermal sensation has a definable sense organ; the thermoreceptors. Thermoreceptors are influenced by a complex array of factors, including ambient temperature, skin temperature and surface area to name a few. Most notable is the methodology used to investigate thermal sensitivity, which can produce confounding results if the techniques used are not fully understood. The ‘methods of limits’ (or ‘thresholds detection’) requires participants to respond to a stimulus once they feel a temperature change. An alternative technique is ‘magnitude estimation’ whereby a participant reports the degree of sensation experienced for a given temperature. As skin temperature and the location and distribution of thermoreceptors vary across the body regional thermal sensitivity to warm or cold stimuli has been shown. However, differences in thermal sensitivity during rest and exercise is particularly important for sports clothing manufactures and gaps in the literature are present when considering this effect. Knowledge of the influence of a warm stimulus on regional sensitivity during exercise is still required.

From the review of the literature the aim of the thesis is to further investigate physiological factors that will influence thermal sensation, thermal comfort and wetness sensation during exercise in moderate to hot conditions. As many factors influence these different perceptions, the literature for each topic will be discussed in detail in the relevant chapters of the thesis.

Chapter three

General methods and methodology

3 Chapter Summary

This chapter describes the experimental research methods used to investigate factors that influence thermal perceptual response during exercise in neutral to hot conditions. The aim of the research is to understand the influence that various physiological responses; skin wettedness (w), galvanic skin conductance (GSC), skin temperature (T_{sk}) and core temperature (T_c) have upon perceptual responses (thermal comfort, thermal sensation and wetness sensation). How these responses vary across body regions will also be investigated. Detailed descriptions of how the generic methods were used are provided in this chapter while methods and procedures specific to single experiments are detailed in the relevant chapter.

3.1 Ethical Clearance

All laboratory methods undertaken have been approved by Loughborough University Ethical committee. Each research proposal was described in detail with an outline of the methodology, procedures and possible risks. The following chapters were approved by the corresponding research proposal number and title:

- Chapter 5, 6, 7, 8 and 9: R10-P27: Investigation of regional skin wettedness and sensations on whole body thermal comfort.
- Chapters 4: G10-P10: ‘Regional sensitivity to a cold and warm stimulus over the body surface

3.1.2 Informed consent and health screen questionnaire

Prior to testing, each participant was provided with a ‘participant information sheet’ informing them of the aims and procedures. Following this they visited the laboratory for a familiarisation session and reminded of the test protocols. They then completed a ‘medical screen questionnaire’ (see Appendix A) to ensure they were capable to undertake the study and signed an ‘informed consent’ form (see Appendix B).

3.1.3 Safety and Withdrawal Criteria

Due to the nature of each experiment and the aims of the investigations, strict withdrawal criteria were followed. Experimental tests were terminated in any of the following conditions:

1. at the discretion of the investigator;
2. at completion of pre-decided duration for exposure;
3. if the participants core temperature rose by 2°C or to an absolute value of 39°C;
4. if average skin temperature rose above 38°C;
5. if participants heart rate rose above 85% of the age predicted heart rate maximum for that participant (85% of (220-age) beats per minute);
6. at the discretion of the participant.

3.2 Participant recruitment

Participants were recruited from the staff and student population of Loughborough University and the age limit was set between 18-45 years to reduce any systemic errors due to age-related differences in thermoregulatory responses. The selection criteria required that all participants were recreationally active to enable them to cope with the physical exertion of the tests. Caucasian European males and females were only recruited to reduce any systematic errors due to ethnic variations in thermoregulation and sensations. Participants were excluded if they failed to meet the standards of health as set down by the Pre-Test Medical Questionnaire, in particular previous heat illness and cardiovascular complications. If the participants had any pre existing conditions which may be exacerbated by taking part in the study then they were excluded.

3.3 Pre-experiment test session

Where required, participants attended the Environmental Ergonomics Research Centre (EERC) to complete a submaximal fitness test and have anthropometric measurements taken. These will be described in detail below.

3.3.1 Submaximal fitness test

A submaximal fitness test was carried out on all participants for each investigation (where stipulated). The purpose of the submaximal fitness test was to estimates individuals aerobic fitness level, expressed as maximal oxygen consumption ($\dot{V}O_{2max}$) using the Astrand-Rhyming method (ACSM, 2006). The test was completed either on a treadmill (WOODWAY PPS Med, WOODWAY Incorporated, Waukesha, WI, USA) or a cycle ergometer (Lode Excalibur 910901, Lode B.V. Medical Technology, Groningen, Nederland) in a thermoneutral environment (~19°C, 40% RH) to prevent any thermal strain. Ambient conditions were monitored using an Eltek/Grant 10Bit, 1000 series Squirrel data logger (Grant Instrument Ltd, Cambridge, UK) and recorded at 1 minute intervals during the trial. Each participant wore a Polar heart rate monitor (Polar Electro Oy, Kemple, Finland), which recorded heart rate at 10 second intervals. Participants were allowed to warm up on the treadmill or cycle ergometer prior to the start of the tests. The warm up was not standardised for each participant but limited to 5 minutes. The test comprised of four 5 minute exercise stages, requiring each participant to exercise for a total of 20 minutes. The test aimed to raise the steady state heart rate of the participant to between 110 beats·min^{-1} to 85% of their age-predicted heart rate max (220-age). The speed of the treadmill was increased by 1.0 km·hr^{-1} every 5 minutes. For the cycle tests, each participant was instructed to pedal at 60 revolutions per minute (RPM) during each stage, with exercise intensity increased every 5 minutes by approximately 20 watts.

The metabolic cost of running at each intensity was calculated in watts (W). The work rate and heart rate during the last 1 minute of each stage was recorded which was used to predict $\dot{V}O_{2max}$. The metabolic cost of running was calculated using the following equation (Epstein et al., 1987):

$$M_r = M_w - 0.5(1 - 0.01 \cdot L) \cdot (M_w - 15 \cdot L - 850)$$

Where;
M_r metabolic cost of running (W)
M_w metabolic cost of walking (W)
L external load (kg)

The metabolic cost of walking (M_w) was calculated using equation developed by Pandolf et al. (1977):

$$M_w = 1.5 \cdot w_b + 2.0\,(w_b + L) \cdot \left(\frac{L}{w_b}\right)^2 + \eta(w_b + L)[1.5 \cdot V^2 + 0.35 \cdot V \cdot G]$$

Where;
w_b body weight of subject (kg)
η terrain factor (η= 1.0 for treadmill)
V speed of walking (m.s-^{1})
G gradient (%)

Using the calculated metabolic rate for each stage, $\dot{V}O_{2max}$ was predicted for each participant in millilitres per kilogram per minute ($ml \cdot kg^{-1} \cdot min^{-1}$) using the following equation:

$$\dot{V}O_2 = \frac{\left[\left(\frac{M_r}{350}\right) \cdot 1000\right]}{w_b}$$

The value of 350 watts based upon the average energy utilized per litre (L) of oxygen consumed (ACSM, 2006). The heart rate for each exercise stage was plotted against predicted $\dot{V}O_2$ using Microsoft Office Excel (2007). A line of best fit was applied to the data and extrapolated to the value corresponding to the participants age predicted heart rate max (220-age). $\dot{V}O_{2max}$ was then predicted from the x-axis.

3.3.2 Anthropometrics measurements

Prior to each investigation the statures of all participants' were measured in cm using a stadiometer and body mass recorded in kg using electronic balance scales (Metter Toledo kcc150, Metter Toledo, Leicester, UK, Resolution 1g). Where stated, skin fold measurements were recorded from the right-hand side of all participants using Holtain Tanner/Whitehouse skinfold callipers (Holtain Ltd. Crymych, Pembs, UK). For makes, the sum of seven skinfold measurement was taken and used to estimate total body density (*Db)* in grams per cubic centimetre (g/cc) and then used to derive total percentage of body fat (%BF). Measurement areas were the triceps, anterior suprailiac, abdomen, thigh, chest, midaxillary, subscapular as defined by Jackson and Pollock (1978). The calculation of *Db* using these seven sites is shown in the following equation:

$$Db = 1.112 - 0.00043499(\sum 7SKF) + 0.00000055(\sum 7SKF)^2 - 0.00028826 \cdot (age)$$

Skinfolds were taken at four sites on the females at the triceps, anterior suprailiac, abdomen and thigh as defined by Jackson et al. (1980) for the calculation of *Db*, using the following equation:

$$Db = 1.096095 - 0.0006952 \cdot (\sum 4SKF) + 0.0000011(\sum 4SKF)^2 - 0.0000714 \cdot (age)$$

Following the calculation of *Db*, body fat percenatge (BF%) was calculated using Siri's equation (Siri 1956, cited in Heyward and Wagner, 2004, p.7):

$$BF(\%) = \left(\frac{4.95}{Db - 4.50}\right) \cdot 100$$

3.4 Experimental session

During each visit, participants pre and post test nude weights were recorded in kg using electronic balance scales (Metter Toledo kcc150, Metter Toledo, Leicester, UK, Resolution 1g) for the assessment of gross sweat loss (GSL). During each trial T_c was measured via rectal thermometer. Participants self inserted a rectal probe 10 cm beyond the anal sphincter. Following this, each participant dressed in the required clothing required for that study. Skin thermistors (Grant Instrument Ltd, Cambridge, UK) were attached to the skin using $3M^{TM}$ $Transpore^{TM}$ surgical tape, (3M United Kingdom PLC) to measure local T_{sk} and calculate $\bar{T}_{sk}$. Humidity sensors (MSR electronics GmbH, Switzerland) were used to measure microclimate *RH* and temperature for the estimation of *w* (as measured by Fukazawa and Havenith, (2009)). They were secured into position using a specially designed holder (see Figure 3.1) that aimed to keep the sensor at an equal distance (5mm either side, with the sensor approximately 2mm from the skin surface) between the skin and clothing across all body measurement sites and glued to the skin using Collodion U.S.P (Mavidon Medical Products, USA). The holder was also designed so that it created a microclimate between the skin and the clothing, without such it would be difficult to measure w_{local}. The location of the sensors depended upon each individual experiment.

Once fully equipped, the participants rested in a thermoneutral environment for 15 minutes to allow physiological responses to stabilise and ensure participants were in a thermally comfortable state. During the rest period the participants were familiarised with the sensation scales and allowed to practise rating their sensations. Following the rest period, participants moved to the chamber to complete the test. Ambient conditions were monitored using a Eltek/Grant 10Bit, 1000 series Squirrel data logger (Grant Instrument Ltd, Cambridge, UK) and recorded at 1 minute intervals during the trial using an Eltek/Grant 10Bit, 1000 series Squirrel data logger (Grant Instrument Ltd, Cambridge, UK). During the last 5 minutes of rest and at 5 minute intervals during exercise participants were asked to rate 3 different sensations for the whole body and individual sites; thermal sensation, wetness sensation and thermal comfort.

Clothing ensembles were weighed pre and post test to establish any sweat absorption in the clothing. All physiological and environmental measurements were recorded at 10 second intervals and 5 minute averages were taken for analysis.

Figure 3.1: The MSR humidity sensors used to measure local skin wettedness. Each sensors is placed in a plastic holder to keep the sensor equal distance from the skin and clothing without restricting air movement around the sensor.

3.5 Calibration

Thermistors, humidity sensors, rectal thermometers and ambient sensors were all calibrated in order to work out the margin of their error. Temperature sensors were verified in a temperature controlled water bath set at a range of temperatures covering the physiological ranges expected from the trials (28, 30, 32, 34 and 36°C) and verified by mercury thermometer. Humidity sensors were calibrated against an Assman hygrometer (4139, Casella, London) and in an environmental chamber covering the physiological ranges expected from the trials (30°C, 30-90% RH). Correction factors were applied to any sensors that had a consistent margin of error and any sensors that had a variable margin of error were replaced.

3.6 Measurement and Calculations

Body weight was measured at the beginning and end of each experimental session to determine gross sweat loss (GSL) in grams (g) and grams per surface area per hour ($g \cdot m^{2} \cdot hr^{-1}$), using the following equations:

$$GSL(g) = W_{\mathrm{bi}} - W_{b2} + fluid$$

$$GSL(\mathrm{g} \cdot \mathrm{m}^{-2} \cdot \mathrm{h}^{-1}) = \frac{\left[\dfrac{\left(w_{bi} - w_{b2} + fluid\right)}{SA}\right]}{t} \cdot 3600$$

Where;

w_{bi} body weight at the start of experiment (kg)

w_{b2} body weight at the end of experiment (kg)

fluid total fluid consumed (kg)

t time duration of experiment (sec)

SA surface area (m^2)

Mean skin temperature ($\bar{T}_{sk}$) and whole body skin wettedness (w_{body}) was calculated using the following equation based on eight measurement sites (Umbach, 1982):

$$Mean\ values = (chest * 0.14) + (abdomen * 0.08) + (upper\ back * 0.11) + (lower\ back * 0.11) + (thigh * 0.2) + (calf * 0.15) + (upper\ arm * 0.12) + (forearm * 0.09)$$

Where only four measurement sites were used, the estimation of $\bar{T}_{sk}$ was calculated using the following equation as proposed by Ramanathan (1964):

$$\bar{T}_{sk} = (0.3 * Tricep) + (0.3 * Chest) + (0.2 * Quadriceps) + (0.2 * Calf)$$

Body temperature (T_b) was estimated using the following calculations of T_c and $\bar{T}_{sk}$ in an 8:2 ratio (Hardy and DuBois, 1938):

$$\bar{T}_b = 0.8 * T_c + 0.2 * \bar{T}_{sk}$$

Local skin wettedness (w_{local}) is defined as the ratio between the maximum evaporation and the actual evaporation for a given environment (Gagge, 1936). It is measured and estimated using the same techniques as described by Fukazawa and Havenith (2009). Local skin wettedness was calculated using the following equation:

$$w = \frac{P_{sk} - P_a}{P_{sk,s} - P_a}$$

Where ;

P_{sk} water vapour pressure at the skin (Pa)

$P_{sk,s}$ saturated water vapour pressure at the skin (Pa)

P_a water vapour pressure of ambient air (Pa)

All physiological data was measured and recorded continuously (recorded at 10 seconds intervals) during the test with 5-minute averages calculated.

3.7 Perception Scales

The scales for the assessment of thermal sensation, wetness sensation and thermal comfort are shown in Table 3.1. Participants were introduced to the sensation scales and instructed how to interpret them and score. They were instructed to rate their sensation at that moment in time and were not permitted to recall their previous sensation, nor were they allowed to use their hands to touch the relevant areas to determine local sensations. They were also instructed to rate their comfort levels based on thermal comfort only and not to base it on factors which may influence them such as the clothing or the sensors attached to their skin.

Table 3.1: Scales used to assess thermal sensation, wetness sensation and thermal comfort.

Thermal sensation	Wetness sensation	Thermal comfort
+10 Extremely hot	0 Dry	0 Comfortable
+9	1	-1
+8 Very hot	2 Moist	-2 Slightly uncomfortable
+7	3	-3
+6 Hot	4 Wet	-4 Uncomfortable
+5	5	-5
+4 Warm	6 Dripping wet	-6 Very uncomfortable
+3		
+2 Slightly Warm		
+1		
0 Neutral		
-1		
-2 Slightly cool		
-3		
-4 Cool		
-5		
-6 Cold		
-7		
-8 Very cold		
-9		
-10 Extremely cold		

Participants were given the following instructions ‘Please rate the sensations of your chest’ after which they would rate the thermal sensation, wetness sensation and thermal comfort in that order for each location. Participants would be prompted to rate their sensations of local body regions in the following order: chest, abdomen, upper back, lower back, upper arms, lower arms, upper legs, lower legs, head and hands. They would finish the sensation by scoring their whole body. They practised this during the pre-test sessions and/or during the rest phase prior to entering the chamber. This would take approximately 1-2 minutes to complete and participants scored the sensation during the last minutes of rest and during exercise at 5-minute intervals.

3.9 Statistical Analysis

Statistical analysis was conducted using the Statistical Package (SPSS) version 18.0. Various different statistical tests are used depending upon the test criteria and these are detailed in each chapter. The analysis of the relationship between the perceptual responses and physiological responses is a consistent theme throughout each chapter. The perceptual responses were treated as interval scales as it was assumed that each point was of equal distance between each descriptor as reinforced with the intermediary numbers. As a result parametric tests were used to analyse any relationships. In some instances multiple regression was performed to determine the best predictor of each sensation. The method of entry for each predictor is stated in the relevant chapters. Due to the nature of the physiological variables measured in each investigation, collinearity amongst the predictors is highly probable. In such cases, a model which best predicts thermal comfort ($r^2>0.80$) using the minimum amount of predictors will be chosen unless otherwise stated. This analysis was carried out on whole body and local sites.

Unless otherwise stated all measurements are expressed as means with standard deviations (± S.D) and significance is defined as $p<0.05$.

Chapter four – Laboratory study 1

Thermal perceptions to a warm stimulus during rest and exercise: A comparison of genders

4 Chapter Summary

Transient (TTS) and steady state (SSTS) thermal sensation to a warm stimulus were investigated during rest and exercise in this chapter. Additionally, the experiment was carried out on both males (n=12) and females (n=12) for a comparison of genders. Each participant was required to rest in a thermoneutral (20°C, 40% RH) room whilst a thermal probe (22 cm^2), set at 40°C, was applied in a balanced order to 31 locations across the body. Participants reported their thermal sensation immediately (transient) and after 10 seconds (steady state). Following this, participants began cycling at 50% $\dot{V}O_{2max}$ for 20 minutes to elevate core temperature (T_c), after this the exercise intensity was lowered to 30% $\dot{V}O_{2max}$ and the sensitivity test repeated. Transient thermal sensitivity (TTS_s) was estimated for each location by dividing TTS by the difference between pre-stimulus skin temperature and stimulus temperature (40°C) (TTS/Tsk_{diff}). Sensitivity areas according to SSTS were determined by the magnitude of the sensation. Body maps were produced for both genders in all conditions, which highlight sensitive areas across the body. Females had a significantly higher magnitude sensation (SSTS) than males at all locations and were significantly more sensitive (TTS_s) than males at some locations across the body. Regional differences in sensitivity and magnitude sensation were evident but were more prominent for females. Magnitude sensation and sensitivity was greatest at the head than the torso and declined towards the extremities. The legs were particularly low sensitive sites in both genders. The data showed that exercise did not cause a significant reduction in TTS_s as scores were similar between rest (0.66 ± 0.3) and exercise (0.61 ± 0.3). Exercise caused a significant reduction in magnitude sensation for males but only at select locations in females. Magnitude sensation significantly reduced after 10 seconds across every location on the body in both genders ($p<0.05$). This is associated with the sensorial overshoot phenomenon for TTS.

4.1 Introduction

Thermal sensation of warmth is a result of the following transient receptor potential vanilloid's (TPRV) being stimulated according to the temperature; TRPV 4 (~25°C), TRPV3 (>33°C), TRPV 2 (>52°C) and TRPV 1 (>42°C). These receptors transiently increase or decrease their firing rates depending upon the direction and magnitude of the change in temperature, which ultimately influences the thermal sensation (Bullock et al. 2001). Regional variations in thermal sensitivity are a result of the location, density and distribution of sensors and although less is known about the distribution of warm thermoreceptors compared to cold, the face is densely populated with both (Lee and Tamura, 1995; Strughold and Porz, 1931, cited in Parsons, 2003, p.59). Due to the regional distribution of thermoreceptors and T_{sk}, researchers have investigated regional sensitivity to thermal stimuli (Stevens et al. 1974; Nakamura et al. 2008, Arens et al. 2005a;b; Ouzzahra et al. 2012). Different methodologies have been employed to investigate regional thermal sensitivity which can produce confounding results if the techniques used are not fully understood. The ‘methods of limits’ (or ‘thresholds detection’) requires participants to respond to a stimulus once they feel a temperature change. An alternative technique is ‘magnitude estimation’ whereby a participant reports the degree of sensation experienced for a given temperature. These methods produce different findings as one location may be sensitive to small temperature changes, but the degree of sensation it experiences for a given stimulus temperature may be lower than other locations. Both techniques can determine the sensitivity across regions, but the type of sensitivity is different so it is important for researchers to define and differentiate between the methods used. The method of limits is affected by the rate of change of temperature and may in part be related to an individual’s reaction time, motor abilities and attention (Hansson et al. 2007). For comparison with Ouzzahra et al. (2012) the present study will focus upon magnitude estimation to warm stimuli, and this will be discussed in more detail here.

Using the magnitude estimation, Ouzzahra et al. (2012) assessed regional distribution of thermal sensitivity to cold during rest and exercise. Their methods involved the application of a cold stimulus (25cm^2 thermal probe) on 16 body locations during rest and exercise. Regional differences were apparent, with the lateral areas of the abdomen and mid back being significantly more sensitive to the cold than medial areas. In a similar study, Stevens et al. (1974) carried out various investigations on regional sensitivity to the warmth. Their methods involved the application of a warm stimulus (thermal irradiance) on up to 10 body regions on 18 males participants, resting in a neutral room (21°C, 50% RH). The stimulus was applied at different strengths and also on different surface areas (3.7–22 cm^2) whilst participants rated the sensation experienced for a given stimulus. They found the larger the area for a given stimulation, the greater the magnitude estimation of warmth. This condition refers to the spatial summation of warmth, in that the sensation is relative to the surface area stimulated. For a given surface area and a given stimulus, Stevens et al. (1974) they were also able to determine regional differences in the following order of high to low sensitivity: forehead, cheek, chest, abdomen, shoulder, back, forearm, upper arm, thigh and calf. Alongside this, Stevens et al. (1974)found that the lower the stimulus level the more pronounced regional differences became, however as the stimulus temperature increased, regional differences tended to diminish. The regional sensitivities' found by Stevens et al. (1974) for thermal sensation agree with those of Nadel et al. (1973), who investigated the influence of regional sensitivity to thermal stimuli as measured by the level of sweating invoked at the thigh in two males. The face was clearly the most sensitive area, followed by the back and abdomen whilst the lower legs were the least sensitive. Nakamura et al. (2008) also investigated regional sensitivity using magnitude estimation by applying either a warm (42°C) or cold stimulus (25°C) using water perfused patches of equal size (0.027 m^2) to the face, chest, abdomen and thigh during mild heat or mild cold exposure during rest. The face is an area known to be densely populated with both warm and cold receptors (Strughold and Porz, 1931, cited in Parsons, 2003, p.59), but interestingly Nakamura et al. (2008) found that the sensitivity of the face to a warm and cold stimulus was only prominent during mild heat exposure and not mild cold exposure. Additionally, it is reported that the chest and abdomen are densely populated with cold spots (Strughold and Porz, 1931, cited in Parsons, 2003, p.59), yet participants were more responsive there to local warming during cold exposure than local cooling during warm exposure. In these circumstances the influence of ambient temperature and the pre-stimulus T_{sk} are likely to be responsible for the de-sensitisation of the thermoreceptors. Nakamura et al. (2008) speculated that the central nervous system assigns weighing factors for each body segment and this is what determines the regional differences in sensitivity rather than receptor density. The weighing factors are related to basic functioning of temperature regulation which must maintain the temperature of the torso and head due to the vital organs located there (Nakamura et al. 2008). This reasoning would support findings from Stevens et al. (1974) and Nadel et al. (1973), as they too found the head and torso to be more sensitive to a warm stimulus than the extremities. This also supports more recent research by Arens et al. (2005a;b) who also used magnitude estimation to investigate regional thermal sensations and comfort in response to microclimate changes in temperature. The results revealed that, in slightly warm and warm conditions, the head region was perceived as the warmest and the overall sensation followed that of the head.

It is well established that the duration of the stimulus has a large influence on the sensation experienced. Early research by Weber (Ross and Murray, 1996) stated that the initial perceptual responses would be exaggerated and over time the perception of temperature would change and become more accurate. This is referred to as an overshoot response, whereby temperature sensations show a tendency to anticipate or initially exceed their final stages, which is common in transient environments (Arens, et al. 2006). It has been claimed that the initial thermal sensation may last for up to 10 seconds, however the rate of change in T_{sk} will strongly influence the sensation evoked (Stevens et al. 1973). This is due to the change in temperature causing the firing rate of receptors to overshoot, sending strong signals to the brain (Hensel, 1981, cited in Li, 2001, p. 41). In support of this, Hensel (1950) suggested that when the skin is exposed to changing temperatures the difference between neutral and the temperature at which hot or cold sensation occurs (i.e. thermal threshold), decreases inversely with the rate at which temperature changed. Although no definite change in temperature or duration of the stimulus has been proposed, it is evident that thermal sensation is rate dependent and also dependent upon initial temperature (Hensel, 1950, cited in Parsons, 2003, p.54).

Gender differences in thermoregulatory responses exist, particularly in heat stress (Cunningham et al. 1978; Davies 1979; Havenith et al. 2008) but limited data currently exist on gender differences in perceptual responses to thermal stimuli. Research indicates that women are more sensitive to pain than males due to gender linked differences in anxiety, gender-role expectations and hormones (Otto and Doygher, 1985; Velle, 1987). Golja et al. (2003) found females to have a lower thermal threshold for both warmth and cold, indicating a higher sensitivity. It has been reported that females have a higher spatial sensitivity and temporal sensitivity than males (Chen et al., 1995; Fillingim et al., 1998). The latter refers to the summation of warmth over time, which has been suggested to be affected by skin thickness, which is thicker in males than females (Sandby-Møller et al. 2003). Spatial sensitivity refers to the summation of warmth for a given area, and thus is influenced by the distribution and density of thermoreceptors. For this reason Lautenbacher and Strian (1991) investigated the relationship of temporal and spatial summation with body surface area and skin thickness between genders. They hypothesised that body morphology is correlated with the density of receptive units in the skin and, as such, with the number of stimulated nerve fibres. They found females were more sensitive to warm thresholds than males at the foot and hand, yet they found no gender linked differences in temporal and spatial summation that could be explained by the differences in body surface area or skin thickness. Golja et al. (2003) and Lautenbacher and Strian (1991) aimed to investigate the temperature thresholds as an indicator of sensitivity utilising the ‘methods of limits’. Research on gender differences has been limited to the method of limits and gender differences have been found, but whether females are more sensitive to the degree of the sensation experienced (using magnitude estimation) is uncertain. Additionally, research investigating gender differences has been limited to one or two body areas (Golja et al. 2003; Lautenbacher and Strian, 1991) thus further research is required to assess regional sensitivity over the body.

A common issue of all the research presented so far, is that thermal sensitivity is assessed on inactive participants. During exercise the thermal state of the body differs to that at rest. Applying a hot stimulus to an individual with either a high or low T_c will result in a different sensation. This response is defined by Cabanac (1969) as thermal alliesthesia; a hedonistic sensation (i.e. pleasure/displeasure) aroused by a given peripheral thermal stimulus is dependent upon the internal state of the subject. In support of this notion, Attia and Engel (1982) found that a thermal pleasant sensation occurred in response to a variety of thermal stimuli when mean T_{sk} and T_c increased during passive heat exposure and exercise. Mower (1976) questioned whether thermal alliesthesia was also applicable to sensation magnitude (i.e. how hot/cold). He found that magnitude sensation is not affected by the thermal state of the body (T_c) but thermal pleasure is. His study was conducted on inactive participants and changes to the internal state of the body were caused by exogenous thermal loads (immersion in a water bath). Whether the changes in magnitude sensation were as a result of endogenous thermal loads (i.e. exercise) has recently been addressed by Ouzzahra et al. (2012). They found a reduction in thermal sensation to a cold stimulus and claimed that the reduction was a result of exercise induced analgesia (EIA). EIA is associated with the activation of the endogenous opioid system during exercise in which various peptides are released that have a similar effect to that of morphine (i.e. they cause a reduction in pain sensitivity) (Beaumont and Hughes, 1979). Work in this field supports this theory as exercise has also been reported to cause a reduction in perceptual responses, particularly tactile and pain sensitivity (Pertovaara et al., 1984; Kemppainen et al., 1986; Kemppainen et al., 1985; Guieu et al., 1992). Large amounts of research exist regarding EIA and pain sensitivity (Pertovaara et al., 1984; Kemppainen et al., 1986; Kemppainen et al., 1985; Guieu et al., 1992) but few studies have investigated thermal sensitivity. Ouzzahra et al. (2012) found males to be significantly more sensitive at rest than during exercise to a cold stimulus at various regions across the body. Paalasma et al. (1991) compared warm and cool thermal sensitivity and heat pain thresholds during two different exercise types; isometric and dynamic exercise. Although there is no comparison to a control group (rest) they did find a load-dependent decrease in sensitivity. Exercise may alter circulating hormones but other basic thermoregulatory responses, such as T_c and T_{sk} change. Paalasma et al. (1991) did not monitor changes in T_c or T_{sk}, which may have provided a simpler explanation of the perceptual responses reported. Whether there is a reduction in sensitivity to a hot stimulus, when T_c is elevated due to exercise, remains unanswered.

Based on all the work discussed above, the present study will elevate T_c with an initial period of exercise in a thermoneutral environment. This will then be followed by a sensitivity protocol carried out at a lower metabolic rate in order to maintain a stable but elevated T_c and reduce the risk of shifting attention away from the thermal stimuli.

4.1.2 Aims

Thermal sensitivity has been studied in depth yet many questions remain unanswered. The most prevalent of these is the influence of exercise on thermal sensitivity to a warm stimulus and that of gender. Therefore, the aims of this investigation are to explore the regional differences in thermal sensitivity to a warm stimulus using magnitude estimation on both males and females during rest and exercise. A transient response and a steady state response to a warm stimulus will also be explored across the body in both genders during rest and exercise.

4.2 Methods

The experimental methodology is outlined in Chapter 3. A summary with specific details to this experiment will be described here.

4.2.1 Participants recruitment

Twelve Caucasian males and twelve Caucasian females from northern European countries were recruited from the staff and student population at Loughborough University.

4.2.2 Experimental Design

The aim of the investigation is to compare sensitivity to a warm stimulus between the following:

- males versus females

- rest versus exercise
- transient versus steady state
- regional variations across the body

To achieve these aims a repeated measures design was opted for, with males and females taking part in both rest and exercise (cycling) while regional thermal sensitivities to a thermal probe at 40°C were investigated. A total of 31 regional body segments were chosen to ensure that each area of the body was fully investigated (detailed later). These included the front and back torso, the arms and legs (upper, lower, front and back), head, face and neck and the extremities. The only areas not investigated were the buttocks and feet due to the clothing and footwear worn during exercise. The testing sequence of the segments was randomised to prevent any order effects. However, the order of rest and exercise in the tests were not randomised as rest had to precede exercise due to the elevation of T_c caused by the latter. This increase could have a lasting effect in any following rest exposures. To counteract any order effect, participants were thoroughly familiarised with the procedure before the start of the actual test.

4.2.3 Clothing

Each participant dressed in the required clothing, which consisted of running shorts, plus sports bra for females and each wore their own personal socks and athletic trainers.

4.2.4 Methodology

Each participant completed a pre-test session for anthropometric measurements; stature, body mass and skin folds thickness. They then completed a submaximal fitness test based on the Astrand Rhyming methods (ACMS, 2006) as outlined in Chapter 3. During the test participants were familiarised with the thermal probe and sensation scales.

For the main trial, pre and post-test nude weight was recorded. Participants self inserted a rectal probe 10 cm beyond the anal sphincter. Following this, dressed in the required clothing, four skin thermistors (Grant Instrument Ltd, Cambridge, UK) were attached at the chest, upper arm, thigh and calf using 3M^{TM} Transpore^{TM} surgical tape, (3M United Kingdom PLC). Markings were then made on the body using a washable pen to indicate each measurement site for the application of the thermal probe. In-depth descriptions of these locations are provided in Table 4.1. Once fully equipped the participant sat in a thermoneutral environment (20°C, 40% RH) for 15 minutes to allow physiological responses to stabilise. During the rest period participants were familiarised with the sensation scales and allowed to practise rating their sensations to a range of warm stimuli across different regions on the body.

After the rest period, thermal sensitivity of each area to a 40°C stimulus was investigated in a balanced order. An area was subjected to the following: the measurement of T_{sk} using an infrared thermometer (FLUKE 566 IR THERMOMETER, Fluke Corporation, Eindhoven, Netherlands), followed by probe application for 10 seconds (Figure 4.1). The temperature controlled thermal probe was similar to that described by Fowler et al. (1987) and that used by Ouzzahra et al. (2012). The thermal probe (NTE-2, Physitemp Instruments, Inc, USA) consisted of a 22 cm^2 metal surface that was controlled at 40°C. The probe was applied to the skin using the pen markings as a reference point. Participants rated their thermal sensation (see Figure 4.2) immediately after probe application which was defined as transient thermal sensation (TTS) and then after 10 seconds, which was defined as steady state thermal sensation (SSTS). This process was repeated for each measurement site. Following the rest period, participants began cycling for 20 minutes at 50% $\dot{V}O_{2\max}$.; after which the exercise intensity was lowered to 30% $\dot{V}O_{2\max}$ to ensure participants maintained a high level of concentration on the thermal ratings whilst still exercising and to create a stable physiological state. The test was then repeated in the same order as the rest condition. Any sweat produced due to exercise was briefly wiped away before the probe was applied. During lower limb assessments, participants ceased exercise whilst the probe was applied and continued thereafter.

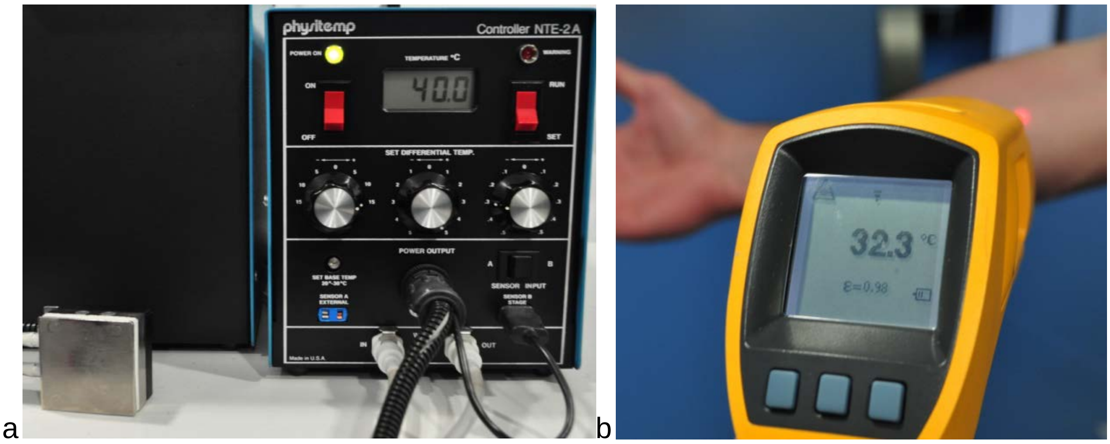


Figure 4.1: a) The thermal probe system set at 40°C. The metal square on the left hand side is the temperature controlled thermal probe. (b)The infrared thermometer used to measure pre stimulus skin temperature.

4.2.5 Measurement areas

Table 4.1 indicates each of the measurement areas, its label and a description of its location. All measurements were taken from the left hand side of the body assuming asymmetry (Claus et al. 1987; Meh and Deništič, 1994). Once located a small mark would be made on the skin with a washable pen. This would serve as the reference point for that location, with the mark being the centre point for the application of the probe. The only exception was the knee and posterior knee whereby the inferior ridge of the probe would be positioned on the markings. The testing sequence of the segments was balanced over participants to prevent any order effects; however the order remained the same during rest and exercise.

4.2.6 Perceptual responses

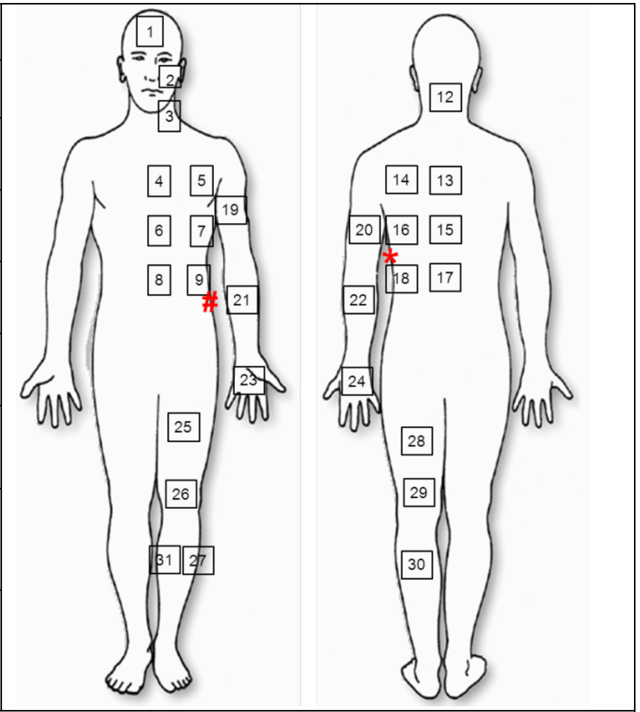
Figure 4.2 shows the scale used to measure thermal sensation. This scale differs to that used elsewhere in this thesis due to planned comparison of the results from this study with other research carried out by Ouzzahra et al. (2012). Participants were introduced to the sensation scales and instructed how to interpret them and score in the pre test session.

Thermal sensation

>10	Painfully hot
10	Extremely hot sensation
9	
8	
7	
6	
5	
4	
3	
2	
1	
0	No hot sensation

Figure 4.2: The thermal sensation scale used for this study.

Table 4.1: The label number, name and description of each measurement area. On the right hand side is an image of the body indicating each measurement area and the corresponding label number. All measurements were taken from the left hand side of the body assuming asymmetry (Claus et al. 1987; Meh and Deništič, 1994).

<table>
<tr><th>Label</th><th>Name</th><th>Description</th><td rowspan="9">
</td></tr>
<tr><td>1</td><td>Forehead</td><td>Half the distance from the bridge of nose to the hairline</td></tr>
<tr><td>2</td><td>Cheek</td><td>Half the distance from the lateral aspect of the nostril to the tragus</td></tr>
<tr><td>3</td><td>Anterior Neck</td><td>Half the distance between the Adams apple and the prominent vertebrae (C7)</td></tr>
<tr><td>4</td><td>Medial Chest</td><td>Half the distance between the lateral edge of the sternum and the nipple</td></tr>
<tr><td>5</td><td>Lateral Chest</td><td>Lateral to the nipple and horizontal to the lateral abdomen (label 9)</td></tr>
<tr><td>6</td><td>Medial torso</td><td>Half the distance between the umbilicus and the xiphoid process, in liner vertically with the medial abdomen (label 8)</td></tr>
<tr><td>7</td><td>Lateral torso</td><td>The point where a vertical line from the lateral abdomen (label 9) meets the horizontal line of the medial torso (label 6)</td></tr>
<tr><td>8</td><td>Medial Abdomen</td><td>3 cm lateral and 1 cm inferior of the umbilicus</td></tr>
<tr><td>9</td><td>Lateral Abdomen</td><td colspan="2">On the horizontal line to the medial abdomen (label 8) and superior to the anterior superior iliac spine</td></tr>
<tr><td>10*</td><td>Midaxillary</td><td colspan="2">At the point where a vertical line from the mid axilla intersects with a horizontal line level with the bottom edge of the xiphoid process</td></tr>
<tr><td>11#</td><td>Suprailiac</td><td colspan="2">Superior to the anterior superior iliac spine on the most lateral aspect</td></tr>
<tr><td>12</td><td>Posterior Neck</td><td colspan="2">Superior to the prominent vertebrae (C7)</td></tr>
<tr><td>13</td><td>Upper Medial Back</td><td colspan="2">Vertical line from the medial chest (label 4) and 3 cm lateral from the vertebral column</td></tr>
<tr><td>14</td><td>Scapula</td><td colspan="2">The point where a vertical line from the medial chest (label 4) meets the horizontal line from the lower lateral back (label 8)</td></tr>
</table>

15	Middle Medial Back	Vertical line from the medial torso (label 7)and 3 cm lateral from the vertebral column
16	Middle Lateral Back	The point where a vertical line from the medial torso (label 7) meets a horizontal line from the lower lateral back (label 18)
17	Lower Medial Back	Horizontal line from the lower lateral back (label 18) and 3 cm lateral from the vertebral column
18	Lower Lateral Back	Superior to the iliac crest
19	Bicep	Half the distance from the superolateral surface of the acromion process to the posterior surface of the olecranon process of the ulna
20	Triceps	At the same distance as the bicep on the posterior aspect of the upper arm
21	Anterior Forearm	Distance from the posterior surface of the olecranon process of the ulna to the styloid process of the ulna
22	Posterior Forearm	At the same distance as the anterior forearm on the posterior aspect of the lower arm
23	Palm	Half the distance from the outer edges of the palm
24	Back of Hand	Half the distance from the outer edges of the hand
25	Quadriceps	Half the distance from the anterior superior iliac spine to the proximal edge of the patella
26	Front of Knee	Proximal edge of the patella
27	Lateral Gastrocnemius	Half the distance from the lateral condyle of the tibia to the lateral malleoli of the fibula
28	Hamstring	At the same distance as the quadriceps on the posterior aspect of the upper leg
29	Posterior Knee	At the height of the distal edge of the patella on the posterior aspect of the leg
30	Posterior Gastrocnemius	At the same distance of the lateral gastrocnemius on the posterior aspect of the lower leg
31	Medial Gastrocnemius	At the same distance of the lateral gastrocnemius on the medial aspect of the lower leg

4.2.7 Thermal sensitivity

Participants rated their thermal sensation immediately after probe application, which was defined as transient thermal sensation (TTS) and then after 10 seconds, which was defined as steady state thermal sensation (SSTS). As thermal sensation is influenced by pre-stimulus skin temperature, the sensitivity of each location will be calculated relative to initial skin temperature. The sensitivity was estimated for TTS by dividing the thermal sensation by the difference between pre-stimulus skin temperature and stimulus temperature (40°C) for TTS (TTS/Tsk_{diff}), which will be designated the following abbreviation; TTS_s. Estimating thermal sensitivity based on Tsk_{diff} allowed for a comparison between locations. This calculated form of sensitivity is only appropriate for TTS and not SSTS due to the length of time (10 seconds) post stimulus that participants are asked to give a perceptual response. After 10 seconds, T_{sk} at each location will likely be at the stimulus temperature of 40°C.

TTS_s indicates the thermal sensitivity and SSTS indicates magnitude sensation. For both terms the higher the number the higher the sensitivity.

4.2.8 Data analysis

Gender differences in TTS_s and SSTS will be analysed using two-way repeated measures ANOVA with gender as a between subject factor. The independent variables included; condition (rest and exercise) and location (n=31) with post hoc comparisons. The large number of locations increases the risk of inflating type I errors when doing multiple post hoc zone comparisons therefore Bonferroni corrections were applied to adjust for this. However this also risked inflating type II errors therefore data corrected and uncorrected for multiple comparisons are presented (Havenith et al. 2008).

4.3 Results

4.3.1 Participants

The physical characteristics of the participants are detailed in Table 4.2. Paired samples t-tests revealed males were significantly taller and heavier than the females. There were no other significant differences between genders.

4.3.2 Body composition

Male and females skinfolds are presented in Table 4.3. At the local sites only the suprailiac was significantly higher for males than females ($p<0.05$), but when corrected for multiple comparison, using Bonferroni, this was no longer significant. The percentage body fat (%BF) for males was estimated based on the sum of 7 skin folds whilst the females were based on sum of 4 skin folds (Jackson and Pollock, 1978; Siri 1956, cited in Heyward and Wagner, 2004, p.7). The % BF for males was 15.0 ± 6.1%, and 22.0 ± 4.2% for females, which is within the normal range for the respective genders.

Table 4.2: Male (n=12) and female (n=12) characteristics (mean ± SD). * Indicates significant difference between genders ($p<0.05$).

	Age (years)	**Mass (kg)**	**Height (cm)**	**$\dot{V}O_{2max}$ (ml·kg·min^{-1})**
Males	20.6 ± 1.0	78.1 ± 15.6*	180 ± 8.9*	34.3 ± 5.2
Females	20.6 ± 1.4	62.9 ± 5.5	167 ± 5.7	36.5 ± 6.6
Mean (± SD)	**20.6 ± 1.2**	**70.5 ±13.8**	**174 ± 10.2**	**34.4 ± 5.8**

Table 4.3: The mean (± SD) skin folds for males (n=12) and females (n=12). The estimation of %body fat was based on the ∑4 skinfolds for females (values in italic) and ∑7 skinfolds for males (values in italics). * Indicates significant difference between genders ($p<0.05$).

Location	Males	Female
Chest	*14.1 ± 7.3*	*12.8 ± 3.4*
Triceps	*18.5 ± 8.1*	*17.1 ± 4.6*
Biceps	*8.5 ± 4.6*	10.6 ± 3.9
Abdomen	*23.9 ± 13.1*	19.2 ± 5.9
Midaxillary	*15.1 ± 5.7*	19.9 ± 6.6
Suprailiac	*32.1 ± 14.3**	19.9 ± 6.6
Subscapular	*13.9 ± 4.1*	12.5 ± 3.0
Thigh	*16.4 ± 6.6*	*19.2 ± 6.0*
Calf	*15.2 ± 9.7*	*13.8 ± 4.3*
Sum of Skinfolds	**∑7=149.1 ± 58**	**∑4=75.4 ± 17.6**

4.3.3 Physiological responses

4.3.3.1 T_c , T_b , T_{sk} and GSL

Mean T_c, T_b and $\bar{T}_{sk}$ and local T_{sk} of each condition are presented in Table 4.4. T_b and $\bar{T}_{sk}$ did not significantly increase with exercise but T_c was significantly higher during exercise for the females only and T_c was significantly higher for females than males.

Metabolic rate during exercise was 97.1 ± 20.7 W for the males and 85.9 ± 17.4 W for the females and they were not significantly different. Median gross sweat loss was 258.5 g for the males and 272.0 g for the females and they were not significantly different ($p>0.05$).

Table 4.4: Mean T_c, T_b and $\bar{T}_{sk}$ (± SD) at rest and during exercise for males (n=12) and females (n=12). # Significant differences ($p<0.05$) between rest and exercise (with Bonferroni correction). * Significant difference ($p<0.05$) between genders with Bonferroni correction.

	Males		Females	
	Rest	Exercise	Rest	Exercise
T_c (°C)	37.4 ± 0.3	37.4 ± 0.5	37.6 ± 0.2$^{\#}$	37.7 ± 0.2*
T_b (°C)	36.0 ± 0.3	36.1 ± 0.5	36.1 ± 0.2	36.2 ± 0.2
$\bar{T}_{sk}$ (°C)	30.2 ± 0.7	30.5 ± 0.9	30.0 ± 0.2	30.2 ± 0.9

Skin temperature was measured at each location prior to stimulation and listed in Table 4.5 and Table 4.6 for males and females respectively. Although Table 4.4 suggests otherwise, T_{sk} measured at the majority of locations using the infrared thermometer was higher during rest than exercise. The difference in T_{sk} may be accounted for in the different measuring techniques used and/or the location of the measurements. Two-way repeated measures ANOVA, with gender as a between subject factor revealed a significant effect of exercise as local T_{sk} was higher during rest than exercise (31.4 ±1.7°C and 30.7 ± 1.8°C, respectively). There was also a significant effect of location ($p<0.05$), but pairwise comparison with Bonferroni revealed no significant differences. This is likely due to the number of comparisons. Table 4.7 shows the results from pairwise comparison without Bonferroni correction), for females (# symbol) and males (* symbol). There was no significant overall effect of gender.

4.3.4 Thermal sensitivity and magnitude sensations

4.3.4.1 Gender differences – Regional variation

Table 4.5 and Table 4.6 list the male and female regional T_{sk}, TTS and SSTS, respectively. Two-way repeated measures ANOVA with gender as a between subject factor was used on both the thermal sensitivity (TTS_s) and magnitude sensation (SSTS) separately.

Table 4.5: Male (n=12) local T_{sk}, transient thermal sensation (TTS) and steady state thermal sensation (SSTS) at rest and during exercise for each location.

		Rest			Exercise		
#	Location	T_{sk} (°C)	TTS	SSTS	T_{sk} (°C)	TTS	SSTS
1	Forehead	32.6 ± 1.9	5.2 ± 2.2	4.1 ± 2.1	31.1 ± 2.0	4.5 ± 2.3	3.2 ± 2.3
2	Cheek	31.4 ± 1.4	5.3 ± 1.9	3.9 ± 2.1	31.0 ± 1.5	4.6 ± 1.9	3.3 ± 2.2
3	Anterior neck	32.5 ± 1.3	4.9 ± 1.9	4.0 ± 1.9	31.7 ± 1.7	4.8 ± 1.7	3.6 ± 1.2
12	Posterior neck	31.5 ± 1.4	4.7 ±2.0	3.8 ± 2.1	31.8 ± 1.5	4.5 ± 2.2	2.7 ± 1.3
4	Medial chest	31.4 ± 1.1	4.8 ± 2.3	3.4 ± 2.1	30.7 ± 1.4	4.4 ± 2.3	2.8 ± 2.2
5	Lateral chest	31.5 ± 1.3	4.5 ± 3.1	3.9 ± 2.4	31.1 ± 1.8	5.0 ± 3.0	3.6 ± 2.2
6	Medial torso	31.3 ± 1.4	5.7 ± 2.1	4.4 ± 2.1	30.5 ± 2.4	5.4 ± 2.7	3.5 ± 2.5
7	Lateral torso	32.3 ± 1.4	5.5 ± 2.3	4.2 ± 2.5	31.8 ± 1.1	5.0 ± 2.4	3.5 ± 2.5
8	Med Abdomen	30.6 ± 2.7	4.9 ± 2.3	3.8 ± 2.2	31.2 ± 1.9	4.7 ± 1.8	2.7 ± 1.6
9	Later abdomen	31.1 ± 1.7	5.4 ± 2.0	4.1 ± 1.9	30.5 ± 1.3	4.8 ± 2.1	2.9 ± 1.9
10	Midaxillary	30.9 ± 1.6	5.6 ± 2.2	4.4 ± 2.5	30.2 ± 1.3	5.1± 1.8	3.0 ± 1.7
11	Suprailiac	31.3 ± 1.2	5.7 ± 2.2	4.3 ± 2.9	30.4 ± 1.8	5.3 ± 2.0	3.8 ± 1.7
13	Up med back	31.3 ± 1.7	6.1 ± 2.2	4.8 ± 2.5	31.1 ± 1.6	5.1 ± 2.4	3.4 ± 2.3
14	Scapula	31.9 ± 1.2	4.9 ± 2.5	3.9 ± 2.6	32.5 ± 1.2	4.5 ± 2.9	3.1 ± 2.2
15	Mid medial back	30.7 ± 2.1	5.3 ± 2.5	4.2 ± 2.6	30.5 ± 1.7	4.7 ± 2.4	2.8 ± 2.1
16	Mid lateral back	31.5 ± 2.2	4.8 ± 2.5	3.7 ± 2.2	31.0 ± 1.4	4.3 ± 2.5	2.9 ±1.9
17	Low med back	31.3 ± 1.2	4.5 ± 2.9	3.4 ± 2.7	30.8 ± 1.8	4.5 ± 2.3	3.1 ± 2.1
18	Low lateral back	31.9 ± 1.2	5.1 ± 2.1	4.3 ± 2.2	31.4 ± 0.9	4.8 ± 2.0	3.3 ± 1.7
19	Biceps	30.9 ± 1.4	5.3 ± 2.1	4.3 ± 2.5	30.4 ± 1.8	5.3 ± 1.6	3.3 ± 1.8
20	Triceps	31.5 ± 1.5	4.7 ± 2.4	3.8 ± 2.1	30.9 ± 1.2	4.6 ± 2.3	2.8 ± 1.8
21	Anterior forearm	31.1 ± 1.5	5.5 ± 2.2	4.3 ± 2.3	30.4 ± 1.7	4.9 ± 1.8	3.7 ± 1.7
22	Posterior f/arm	31.3 ± 1.3	4.5 ± 2.5	3.5 ± 2.8	30.3 ± 1.6	4.6 ± 2.3	3.1 ± 2.3
23	Palm	31.4 ± 1.5	5.3 ± 2.8	4.0 ± 2.3	31.1 ± 1.6	4.6 ± 2.6	3.3 ± 2.0
24	Back of hand	30.4 ± 2.1	5.1 ± 2.3	4.0 ± 3.0	30.5 ± 1.8	4.8 ± 2.4	3.2 ± 2.0
25	Quadriceps	32.2 ± 1.1	5.4 ± 2.1	4.1 ± 2.6	31.6 ± 1.1	5.3 ± 2.3	3.8 ± 2.3
26	Front knee	30.7 ± 1.5	5.3 ± 2.4	3.9 ± 2.3	30.2 ± 2.4	4.3 ± 2.8	2.8 ± 2.1
27	Lat calf	31.1 ± 1.7	5.2 ± 2.5	4.2 ± 2.0	30.9 ± 0.8	5.1 ± 1.9	3.6 ± 2.1
28	Hamstring	30.8 ± 1.4	5.7 ± 2.3	4.3 ± 3.0	30.2 ± 1.4	5.0 ± 2.4	3.3 ± 2.1
29	Posterior knee	31.9 ± 1.2	5.5 ± 2.4	4.6 ± 2.7	30.8 ± 1.9	4.8 ± 1.8	3.7 ± 2.2
30	Post calf	30.8 ± 1.8	5.1 ± 2.1	3.9 ± 2.5	30.2 ± 1.4	4.0 ± 2.1	2.8 ± 2.1
31	Med calf	30.4 ± 1.3	4.7± 1.7	3.7 ± 2.1	30.4 ± 1.2	3.3 ± 2.1	2.2 ± 1.6
	Mean	**31.3 ± 1.6**	**5.2 ± 2.2**	**4.0 ± 2.3**	**30.9 ± 1.6**	**4.7 ± 2.2**	**3.2 ± 1.9**

Table 4.6: Female (n=12) local T_{sk}, transient thermal sensation (TTS) and steady state thermal sensation (SSTS) at rest and during exercise for each location.

		Rest			Exercise		
#	Location	T_{sk} (°C)	TTS	SSTS	T_{sk} (°C)	TTS	SSTS
1	Forehead	34.3 ± 0.3	5.4 ± 1.9	4.5 ± 1.7	33.1 ± 1.2	6.5 ± 2.1	5.1 ± 1.9
2	Cheek	32.2 ± 1.0	6.3 ± 1.6	5.8 ± 1.8	33.1 ± 2.0	6.7 ± 2.0	4.8 ± 2.2
3	Anterior neck	33.6 ± 0.5	6.8 ± 1.3	5.2 ± 1.4	32.0 ± 1.6	7.1 ± 1.7	5.2 ± 1.7
12	Posterior neck	33.6 ± 1.0	6.4 ± 1.4	4.9 ± 1.7	31.9 ± 1.4	6.8 ± 1.3	5.3 ± 1.5
4	Medial chest	32.9 ± 1.1	6.7 ± 1.8	5.3 ± 1.4	31.7 ± 1.1	6.7 ± 1.6	4.8 ± 1.8
5	Lateral chest	32.5 ± 0.8	6.3 ± 1.9	5.2 ± 1.9	30.4 ± 1.4	6.7 ± 1.2	4.8 ± 1.9
6	Medial torso	32.4 ± 1.2	6.0 ± 1.7	4.8 ± 2.1	30.1 ± 1.6	6.6 ± 1.8	4.5 ± 2.0
7	Lateral torso	33.0 ± 0.7	6.8 ± 1.5	5.7 ± 1.8	31.0 ± 1.0	7.0 ± 1.4	4.9 ± 1.8
8	Med Abdomen	30.9 ± 0.9	6.2 ± 1.6	5.3 ± 2.0	28.0 ± 1.2	6.2 ± 1.6	4.1 ± 1.9
9	Later abdomen	32.6 ± 1.3	6.7 ± 1.2	5.5 ± 1.5	30.4 ± 1.1	6.9 ± 1.6	5.1 ± 2.0
10	Midaxillary	31.6 ± 0.8	6.4 ± 1.3	4.8 ± 1.1	30.3 ± 0.9	7.0 ± 1.6	4.9 ± 1.8
11	Suprailiac	30.2 ± 1.6	6.6 ± 1.6	5.3 ± 2.3	29.1 ± 1.2	6.1 ± 2.0	4.4 ± 2.2
13	Up med back	33.1 ± 1.2	6.3 ± 1.7	5.1 ± 2.0	31.4 ± 1.2	6.3 ± 2.0	5.1 ± 1.7
14	Scapula	32.2 ± 0.9	5.0 ± 1.8	3.9 ± 1.8	30.6 ± 1.3	5.8 ± 2.1	3.5 ± 1.5
15	Mid medial back	31.9 ± 1.5	6.6 ± 1.6	5.4 ± 2.1	29.9 ± 1.8	6.5 ± 1.6	4.3 ± 2.0
16	Mid lateral back	31.3 ± 1.5	7.2 ± 1.2	5.8 ± 1.7	29.7 ± 1.5	7.0 ± 1.5	5.2 ± 1.6
17	Low med back	31.4 ± 1.1	6.3 ± 2.0	5.6 ± 2.3	29.3 ± 1.7	7.2 ± 1.5	5.1 ± 1.9
18	Low lateral back	30.0 ± 1.1	6.7 ± 1.8	5.3 ± 2.0	28.8 ± 1.5	6.7 ± 1.7	5.1 ± 2.2
19	Biceps	31.0 ± 0.6	5.5 ± 1.4	4.5 ± 1.6	30.3 ± 1.2	6.0 ± 1.7	4.4 ± 2.1
20	Triceps	29.2 ± 0.6	5.6 ± 1.4	4.5 ± 1.2	30.2 ± 1.4	6.0 ± 1.8	4.3 ± 1.7
21	Anterior forearm	32.2 ± 0.9	6.0 ± 2.0	5.0 ± 2.1	31.1 ± 1.4	6.1 ± 2.2	4.8 ± 2.0
22	Posterior f/arm	31.1 ± 0.8	5.1 ± 1.3	3.9 ± 1.5	30.9 ± 1.3	5.0 ± 1.7	3.5 ± 1.6
23	Palm	32.3 ± 1.8	4.8 ± 2.0	4.1 ± 2.1	33.2 ± 1.2	5.7 ± 2.2	5.1 ± 2.5
24	Back of hand	31.4 ± 2.2	4.9 ± 1.3	4.4 ± 1.9	32.2 ± 1.4	5.9 ± 2.2	5.1 ± 2.6
25	Quadriceps	30.7 ± 1.0	5.9 ± 1.8	4.8 ± 2.3	30.1 ± 1.0	6.3 ± 1.4	4.3 ± 1.8
26	Front knee	28.7 ± 0.5	5.3 ± 1.8	4.3 ± 1.2	30.0 ± 1.7	5.9 ± 1.0	4.7 ± 1.3
27	Lat gastrocnemius	30.0 ± 0.7	4.8 ± 1.8	3.8 ± 1.6	29.5 ± 1.1	4.8 ± 1.9	3.9 ± 1.6
28	Hamstring	29.9 ± 1.1	6.3 ± 1.1	5.3 ± 1.3	28.3 ± 1.1	6.2 ± 1.5	4.8 ± 1.7
29	Posterior knee	32.7 ± 1.3	5.1 ± 1.6	4.1 ± 1.7	29.9 ± 1.0	5.5 ± 1.3	4.0 ± 1.1
30	Post gastrocnemius	29.4 ± 0.6	4.8 ± 1.8	3.9 ± 1.4	28.1 ± 1.0	4.7 ± 1.9	3.0 ± 1.4
31	Med gastrocnemius	29.4 ± 0.6	5.8 ± 1.5	5.3 ± 1.8	29.2 ± 0.8	5.3 ± 1.5	3.9 ± 1.9
	Mean	**31.5 ± 1.4**	**5.9 ± 1.7**	**4.9 ± 1.8**	**30.4 ± 1.9**	**6.2 ± 1.8**	**4.6 ± 1.9**

Table 4.7: Significance of pairwise comparison between locations for female T_{sk} (#p<0.05, ##p<0.001, without Bonferroni corrections) and male T_{sk} (*p<0.05 without Bonferroni corrections). No significant pairwise comparisons were found with Bonferroni corrections

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
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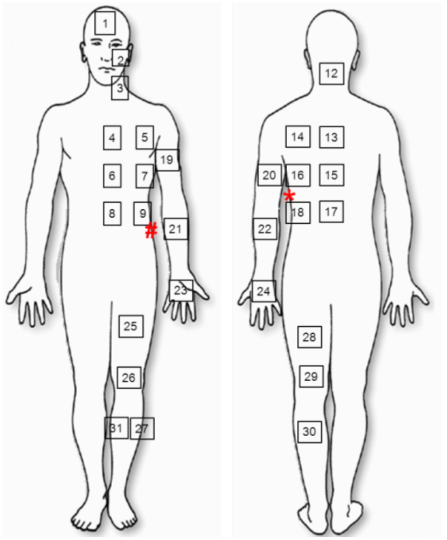

Table 4.8: Significance of pairwise comparison between locations for female TTSs (*p<0.05 and **<0.001 with Bonferroni correction) (░ <0.05 and ▓ p<0.001, without corrections) and female SSTS (+p<0.05, ++p<0.001, with Bonferonni corrections; #p<0.05).

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
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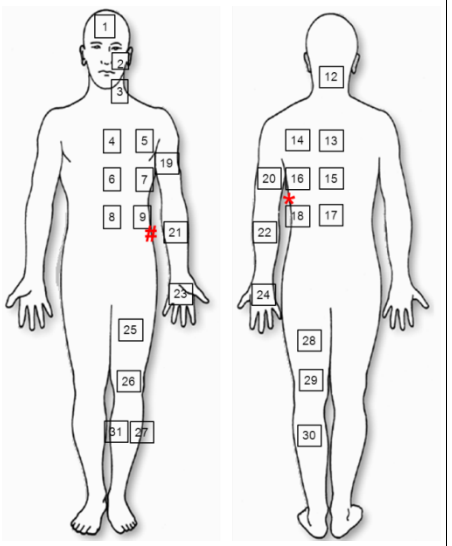


Thermal sensitivity - TTS$_s$

Male and female TTS$_s$ are illustrated in Figure 4.3 and Figure 4.4 respectively. The females had a higher mean sensitivity score (0.70 ± 0.3 and 0.57 ± 0.3, respectively), yet the results revealed no significant overall effect of gender ($p>0.05$). No significant overall effect of condition was found as scores were similar between rest (0.66 ± 0.3) and exercise (0.61 ± 0.3).

A significant interaction occurred between gender and location and significant post hoc comparisons are indicated in Figure 4.3 (values underlined). The lateral torso was a highly sensitive area in both males and females during rest and exercise, as was the upper medial back, hand and palm. The lower legs were the least sensitive areas for both genders.

Overall the main findings were:

- *Head* - females were significantly more sensitive than males on all areas of the head;
- *Front torso* - females were significantly more sensitive than males on the lateral aspects of the front torso and at the medial chest;
- *Back torso* - females were significantly more sensitive than males on the middle back and medial lower back;
- *Hands and arms* - females were significantly more sensitive than males at the anterior forearm, hand and palm;
- *Legs* - the legs were the least sensitive area for both genders and there were no significant differences between males and females.

When analysed separately by gender, the results indicated a significant effect of condition and time. No significant overall effect of location was found for males but a significant overall effect of location for females. Female pairwise comparisons are highlighted in Table 4.8 and the regional differences for each area are:

- *Head* - areas within the head region were significantly more sensitive than most locations across the body;
- *Front torso* - sensitivity decreases lateral-medial, except at the chest. The medial abdomen is the least sensitive area within this region and was significantly lower to most areas in the front torso and head region;
- *Back torso* - within the back torso, the upper back contains the most and least sensitive area (upper medial back and scapula, respectively);

- *Arms and hands* - the forearm contains the least and most (along with the palm and hand) sensitive area in this region. Sensitivity was highest on the anterior aspect and lowest on the posterior aspect of the arms;
- *Legs* - sensitivity decreases proximal-distal as the upper legs are more sensitive than the lower legs. The back of the knee is the most sensitive area within this region. The medial and posterior gastrocnemius are significantly less sensitive than most locations across the body.

Magnitude sensation - SSTS

Male and female SSTS are illustrated in Figure 4.5 and Figure 4.6, respectively. A significant overall effect of gender was observed for SSTS as females scored a higher sensation score than males (4.7 and 3.6, $p<0.05$, respectively). A significant overall effect of condition was found as thermal sensation was higher during rest than exercise (4.4 and 3.9, respectively). A significant overall effect of location was observed ($p<0.05$) and a significant interaction between gender and location ($p<0.05$). Due to the large number of comparisons, the data was checked with and without Bonferroni corrections. Without corrections, the results revealed that each location was significantly higher for females than males. When analysed separately, the results indicated no significant overall effect of location for males but a significant overall effect for females. Female pairwise comparisons are highlighted in Table 4.8 and the regional differences for each area are:

- *Head* - there is little variation between zones; the cheek however has a higher sensation than all locations across the body. The areas within the head have significantly higher sensations than areas within the legs (without Bonferroni corrections);
- *Front torso* - no significant differences were observed within the front torso but the lateral aspect had higher values than medial parts. Regional differences tend to diminish with exercise;
- *Back torso* - within the back torso area, the scapula scored the lowest sensation whilst the middle lateral back and lower medial back scored the highest;
- *Arms and hands* - the posterior forearm had the highest sensation score within this region and was significantly lower than other locations across the body. Sensation at the hand and palm increased with exercise compared to rest;
- *Legs* - sensation decreases proximal-distal as the upper legs were generally scored higher sensations than the lower leg. The lower legs are significantly

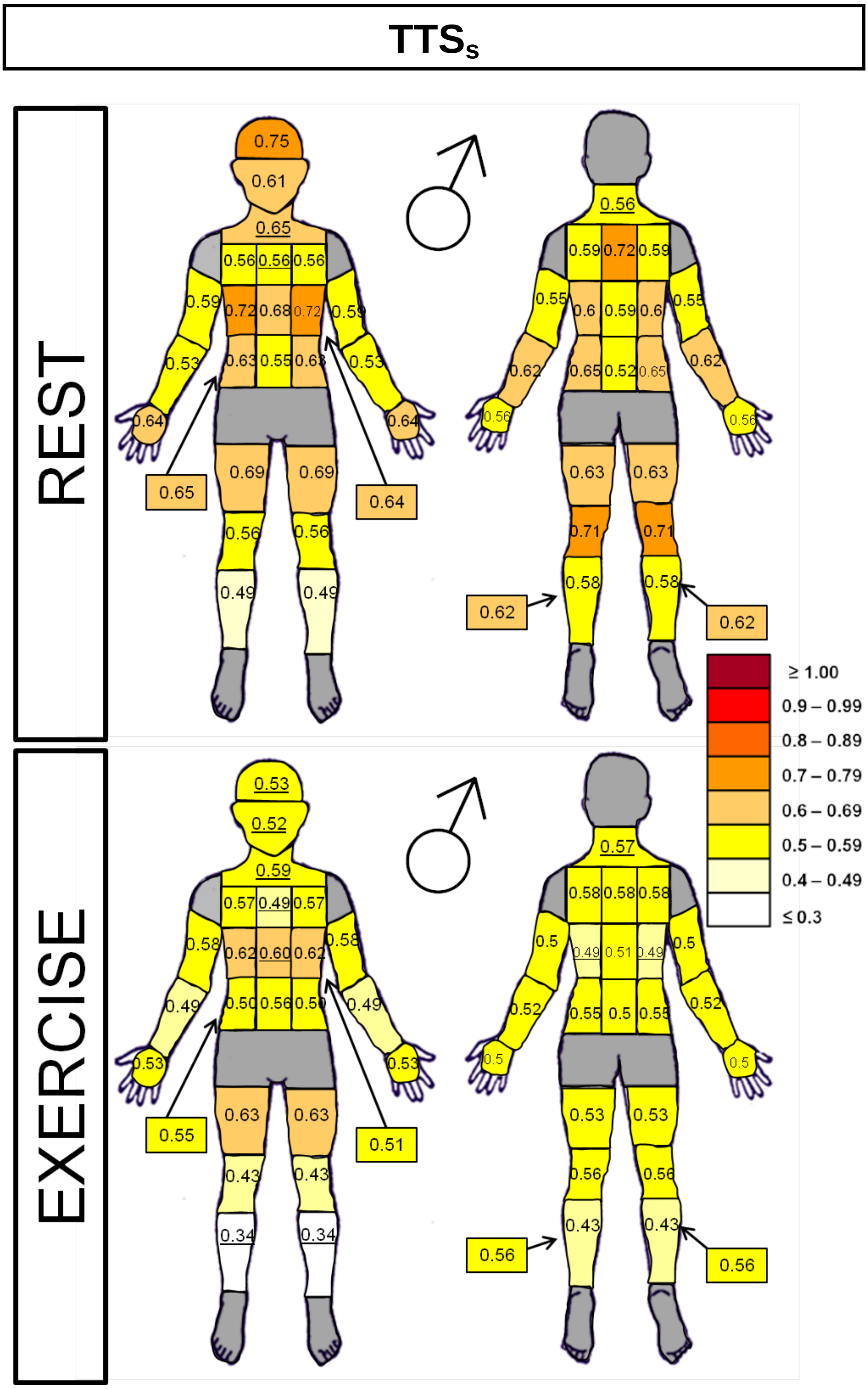


Figure 4.3: Males (n=12) regional transient thermal sensitivity (TTS_s) to a warm stimulus (40°C) during rest and exercise. ($TTS_s = TTS/\Delta T_{sk}$). Values underlined indicate significant difference to female TTS_s ($p<0.05$). All measurements were taken from the left hand side of the body assuming asymmetry (Claus et al. 1987; Meh and Deništič, 1994). Areas in black were not investigated

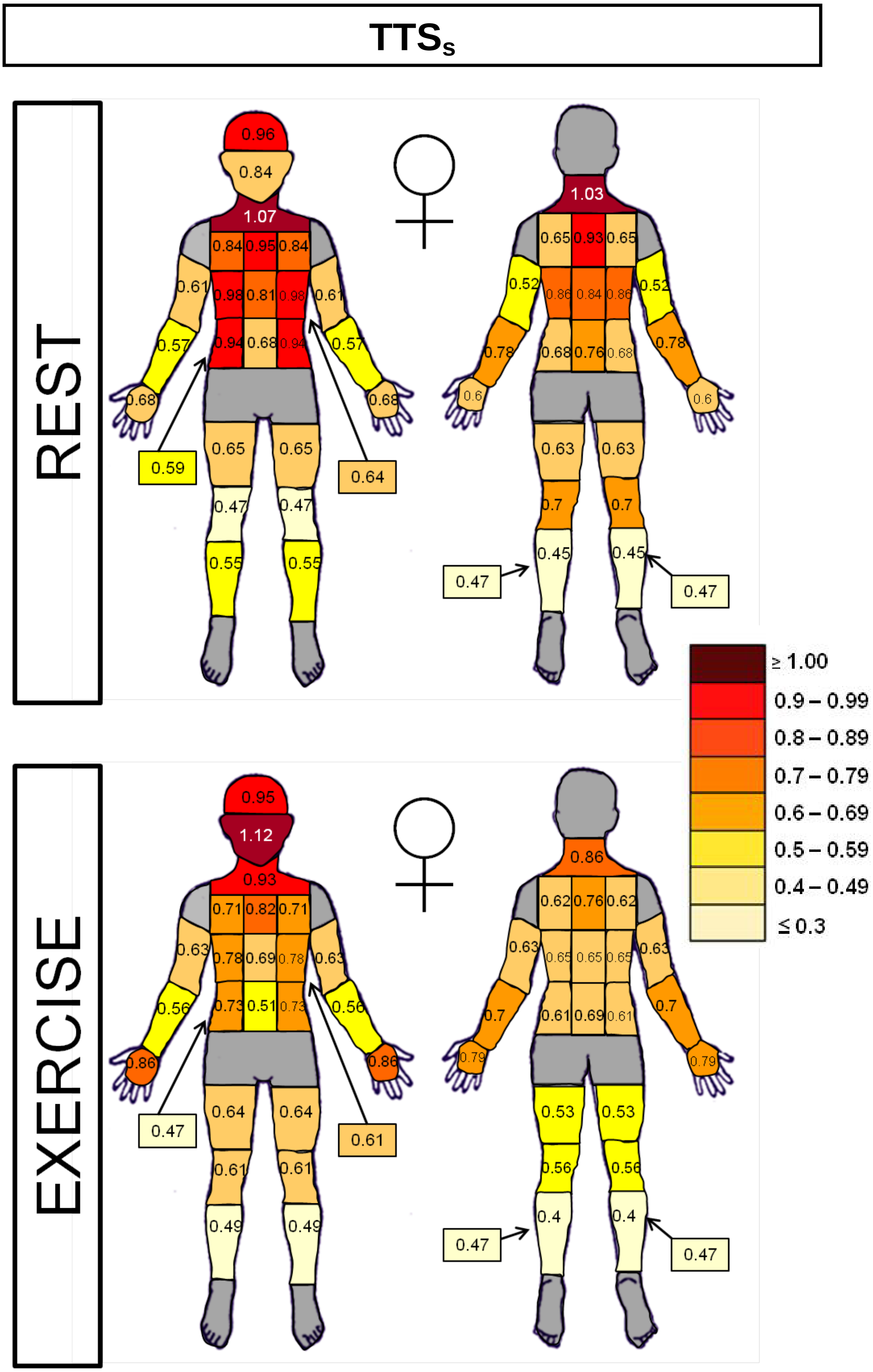


Figure 4.4: Female regional transient thermal sensitivity (TTS$_s$) to a warm stimulus (40°C) during rest and exercise. ($TTS_s = TTS/\Delta T_{sk}$). All measurements were taken from the left hand side of the body assuming asymmetry (Claus et al. 1987; Meh and Deništič, 1994). Areas in black were not investigated

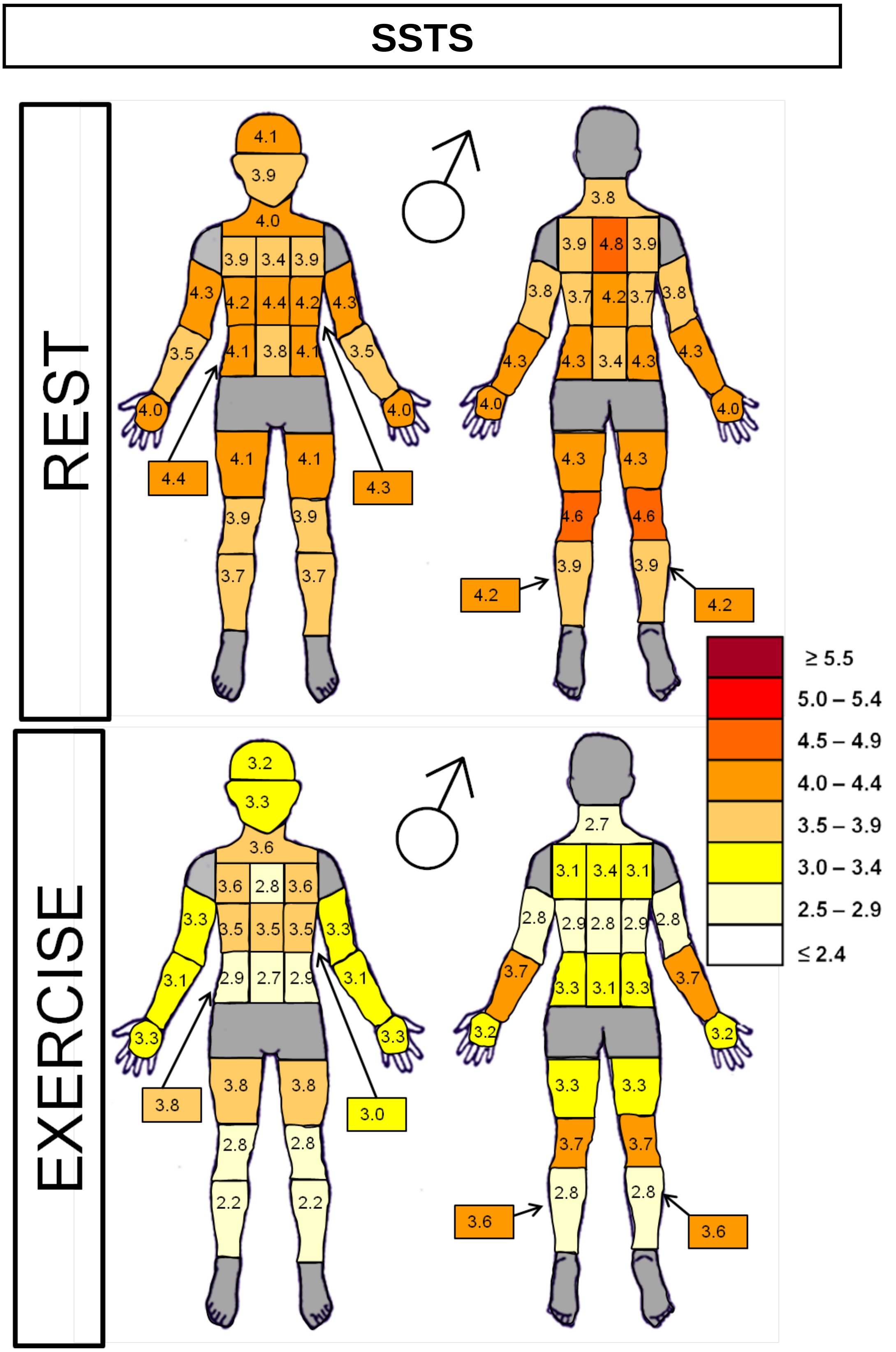


Figure 4.5: Male regional steady state sensitivity (SSTS) to a warm stimulus (40°C) during rest and exercise. All areas were significantly lower than females (p<0.05). All measurements were taken from the left hand side of the body assuming asymmetry (Claus et al. 1987; Meh and Deništič, 1994). Areas in black were not investigated

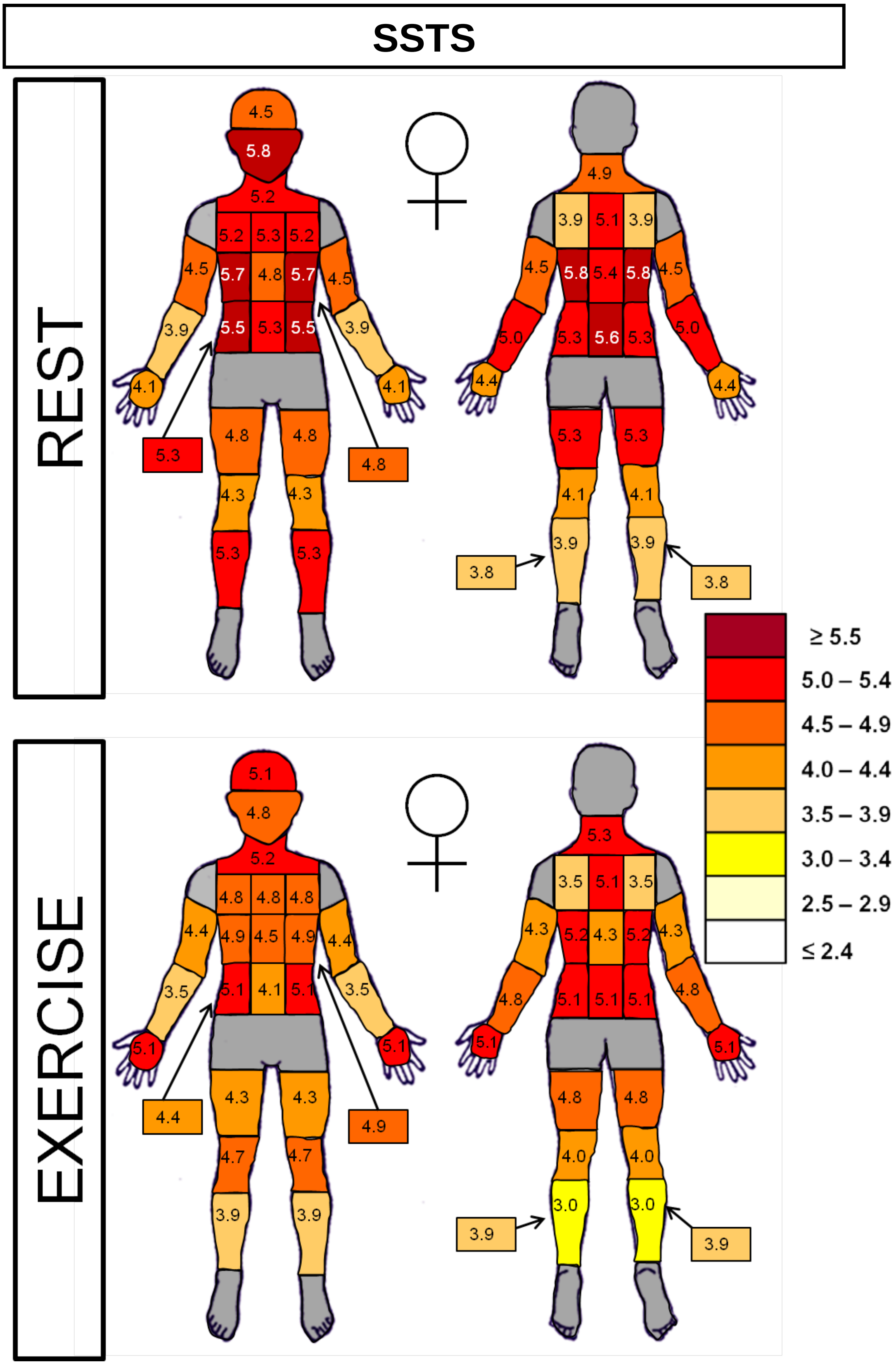


Figure 4.6: Female regional steady state sensitivity (SSTS) to a warm stimulus (40°C) during rest and exercise. All areas were significantly higher than males ($p<0.05$). All measurements were taken from the left hand side of the body assuming asymmetry (Claus et al. 1987; Meh and Deništič, 1994). Areas in black were not investigated.

lower than most locations across the body. The anterior aspects of the leg generally had a higher warmth sensation score than the posterior.

Main finding:

- females were significant more sensitive (TTSs) than males at some locations;
- females had more regional differences in sensitivity than males; the head was more sensitive than the torso and the torso was more sensitive than the extremities;
- females scored a significantly higher magnitude sensation (SSTS) than males;
- exercise causes a significant reduction in magnitude sensation on both genders.

4.3.6 Rest versus Exercise

As stated earlier, TTS$_s$ and SSTS were higher during rest than for almost all locations in both genders. The differences between rest and exercise for each location and the significant differences are displayed in Table 4.9; the larger the number the bigger the difference between rest and exercise. For TTS$_s$ and SSTS the males had the largest differences between rest and exercise and thus more significant differences for TTSs (9 out of 31) and SSTS (15 of 31). The differences were less pronounced in females for TTSs (0 out of 31) and SSTS (6 out of 31). In both groups, the largest differences between rest and exercise were at the lower legs. Negative numbers in Table 4.9 indicate where sensitivity increased with exercise, though none of these are significant.

Main finding:

- exercise causes a reduction in sensitivity and magnitude sensation in both genders.

4.3.7 TTS versus SSTS

TTS and SSTS for males and females are listed in Table 4.5 and Table 4.6, respectively. TTS was higher than SSTS for all locations in both genders, indicating sensation magnitude declines with time. Individual paired t-tests (with and without Bonferroni corrections) were carried out to analyse the difference between the raw data of each location for TTS and SSTS. The results are displayed in Table 4.10 (the

Table 4.9: The differences in thermal sensation between rest and exercise for each location in males (n=12) and females (n=12). * $p<0.05$ (without Bonferroni corrections). No significant differences with Bonferroni correction.

Location	**ΔTTS_s (rest-exercise)**		**$\Delta SSTS$ (rest-exercise)**	
	Females	**Males**	**Females**	**Males**
Forehead	0.0	0.21*	-0.6	0.9*
Cheek	-0.28	0.09	1.0	0.7*
Anterior neck	0.15	0.07*	0.0	0.4
Posterior neck	0.16	-0.01	-0.3	1.2*
Medial chest	0.13	0.07	0.4	0.7
Lateral chest	0.14	-0.01	0.3	0.3
Medial torso	0.11	0.08	0.3	0.9
Lateral torso	0.19	0.10	0.8*	0.7*
Medial abdomen	0.17	-0.01	1.2*	1.1
Lat abdomen	0.21	0.12*	0.4	1.2*
Midaxillary	0.03	0.13	-0.1	1.4*
Suprailiac	0.11	0.10	0.9*	0.5
Upper medial back	0.18	0.14	0.00	1.4*
Scapula	0.03	0.01	0.4	0.8
Middle medial back	0.18	0.09	1.2*	1.4*
Middle lateral back	0.17	0.11	0.7	0.8
Lower medial back	0.07	0.02	0.5	0.3
Lower lateral back	0.07	0.09	0.2	1.0*
Biceps	-0.01	0.02	0.1	1.0
Triceps	-0.11	0.05	0.3	0.9*
Anterior forearm	0.09	0.09*	0.3	0.7
Posterior forearm	0.01	0.04	0.4*	0.3
Palm	-0.18	0.11	-1.0	0.8
Back of hand	-0.18	0.07	-0.7	0.7*
Quadriceps	0.01	0.07	0.4	0.3
Front knee	-0.14	0.13*	-0.4	1.2*
Lateral gastrocnemius	0.01	0.06	-0.1	0.6
Hamstring	0.10	0.11*	0.5	1.0*
Posterior knee	0.15	0.15*	0.1	0.9
Post. gastrocnemius	0.05	0.15*	0.9*	1.2*
Medial gastrocnemius	0.05	0.15*	1.4*	1.5*
Overall mean	**0.05**	**0.08**	**0.31**	**0.86***

larger the number the bigger the difference between TTS and SSTS). The torso area had the largest decrease in sensation scored from TTS to SSTS, whilst the smallest change was within the leg regions for both genders. The palm and back of the hand for the females had the lowest difference in sensitivity.

Table 4.10: The differences in thermal sensation (∆TS) between TTS and SSTS for each location in males (n=12) and females (n=12). Thermal sensitivity is based on the mean of TTS and SSTS during rest and exercise. # p<0.05, ## p<0.001 with Bonferroni correction, * p<0.05, ** p<0.001 without Bonferroni corrections.

Location	**∆TS (TTS-SSTS)**	
	Females	Males
Forehead	1.17**##	1.21**##
Cheek	1.17**##	1.33**##
Anterior neck	1.79**##	1.08**##
Posterior neck	1.54**##	1.33**##
Medial chest	1.63**##	1.50**##
Lateral chest	1.46**##	1.00**##
Medial torso	1.63**##	1.58**##
Lateral torso	1.58**##	1.42**##
Medial abdomen	1.50**##	1.58**##
Lat abdomen	1.50**##	1.58**##
Midaxillary	1.85**##	1.63**##
Suprailiac	1.50**##	1.46**##
Upper medial back	1.21**##	1.46**##
Scapula	1.67**##	1.21**##
Middle medial back	1.71**##	1.54**##
Middle lateral back	1.58**##	1.29**##
Lower medial back	1.42**##	1.25**##
Lower lateral back	1.50**##	1.17**##
Biceps	1.29**##	1.50**##
Triceps	1.42**##	1.33**##
Anterior forearm	1.17**##	1.21**##
Posterior forearm	1.33**##	1.25**##
Palm	0.67*	1.33**##
Back of hand	0.67*	1.25**##
Quadriceps	1.54**##	1.42**##
Front knee	1.13**##	1.46**##
Lateral gastrocnemius	0.88**##	1.25**##
Hamstring	1.25**##	1.50**##
Posterior knee	1.25**##	1.04**##
Post. gastrocnemius	1.25**##	1.21**##
Medial gastrocnemius	0.88*	1.04**##
Overall mean	**1.36**##**	**1.34**##**

Main finding:

- sensation magnitude decline with time in both genders.

4.4 Discussion

The aim of this study was to investigate gender differences in transient and steady state thermal sensation to a warm stimulus (40°C) during rest and exercise. The study also aimed to provide a detailed description of regional sensitivity from multiple locations across the whole body. The main findings from this investigation were:

- females had a stronger magnitude sensation (SSTS) than males to a hot stimulus (40°C);
- exercise reduces magnitude sensation to a hot thermal stimulus (40°C) in males but only at select locations for females;
- sensation magnitude declines with time;
- regional variations in sensation exist for both genders, but it is more prominent for females.

Participants were semi-nude in a thermoneutral room and T_{sk} was not clamped, but allowed to vary naturally. The pattern of T_{sk} across the body was as to be expected with the head T_{sk} being the highest, followed by the torso then the extremities (Clark et al. 1977). During exercise, T_{sk} decreased most likely due to initial sympathetic vasoconstriction followed by sweat evaporation. The T_{sk} pattern during exercise remained the same as during rest.

4.4.1 Gender differences

Gender differences in thermoregulatory responses exist, particularly in response to heat stress (Cunningham et al. 1978; Davies 1979; Havenith et al. 2008) but thermal sensitivity research is generally limited to male participants (Arens et al. 2005; Cotter and Taylor, 2005; Nakamura et al. 2008; Ouzzahra et al. 2012). The present study compared male and female thermal sensation responses to a hot stimulus and despite different findings for TTS_s and SSTS; overall females were more sensitive than males. TTS_s at all locations were higher for females than males, but there was no significant overall effect of gender. SSTS was also higher for females than males at each location and this time analysis revealed a significant overall effect of gender. Significant interactions were observed between gender and location for both TTS_s and SSTS indicating regional variation between genders. Post hoc analysis revealed that females have a significantly stronger magnitude sensation (SSTS) than males at all locations but only in some locations for TTS_s. These will be discussed in the next section (Regional differences). According to Inoue et al. *(*2005) females produce less sweat than males and therefore rely upon convective heat loss more than evaporative heat loss. Therefore, it would be beneficial for females to be more sensitive to a heat stimulus than males in order to encourage behavioural responses to maintain thermal balance.

The findings of the present study agree with previous studies who also found females to be significantly more sensitive than males to heat (Golja et al. 2003; Lautenbacher and Strain, 1991; Kenshalo, 1986). These studies compared one or two sites and employed the ‘methods of limits’ which required participants to state when they detect a temperature change. This technique allows temperature thresholds to be determined, which can be very small (<1.0°C). Method of limits consistently influences temporal summation (i.e. summation of warmth over time) as the thermal stimuli always changes until it is detected. Previous research by Filingim et al. (1998) found that females have a greater temporal summation for thermal pain than males. In the present study, SSTS was rated after 10 seconds which can be associated with temporal summation and thus explain why a significant effect of gender was observed for SSTS and not TTS_s. Reasons as to why no significant gender differences existed for TTS_s may be associated with the temperature of the stimulus. Much of the gender linked differences reported in the literature have been in studies of thermal pain sensitivity (Filingim et al. 1998; Lautenbacher and Strain, 1991) but the stimuli used in the present study (40°C) was specifically chosen not to stimulate noxious thermal pain (TRPV1; >42°C) but rather TRPV3, which responds to temperatures >33°C. Significant differences between genders for TTS_s may be more prominent if the stimuli was either close to local T_{sk} or >42°C and thus stimulating TRPV1.

4.4.2 Regional differences

At each location SSTS was always significantly higher for females than males. Additionally, only for females a significant overall effect of location was observed. Based on these two findings the following section on regional differences will focus upon TTS_s and female sensitivity, unless stated otherwise.

Head region

Thermoreceptor density and location is not uniform across the body, nor is the pattern of T_{sk}, as a result it was unsurprising to observe regional variations in thermal sensitivity. Regional variation exists for both genders, but the analysis indicated a significant overall effect of location for the females only. In agreement with the literature, the overall pattern of sensitivity is greatest at the head and the torso and lowest at the extremities. For females the areas around the head were significantly more sensitive than a large number of other locations, but particularly areas within the leg region. The head has consistently been defined as a sensitive area due to the large number of thermoreceptors and the importance of keeping the brain within a thermo-prescriptive zone (Strughold and Porz, 1931, cited in Parsons, p59; Nadel et al. 1973; Cabanac, 1993; Nagasaka et al., 1998). Overall, sensitivity was greatest in the head region than any other location across the body. The forehead is in close proximity to the brain and the anterior neck consists of a large network of blood vessels supplying oxygenated blood to the brain. The temperature of the blood is detected by the anterior-hypothalamus and provides feedback regarding the thermal state of the body. In the interest of protecting the brain from overheating, the area of the forehead and anterior neck ought to be of high sensitivity to initiate behavioural and/or physiological responses to maintain a safe internal environment.

Torso region

The torso also contains vital organs and research has shown this to be an area less sensitive than the face but more sensitive than the extremities for various other parameters than studied here (Nadel et al. 1973; Nakamura et al., 2008; Stevens et al. 1974; Cotter and Taylor, 2005; Arens et al. 2005). The findings from the present study are in agreement with the literature as areas within the front torso were significantly more sensitive than areas within the leg region (for females). Despite no significant overall effect of location for the males, regional differences followed a similar pattern to the females. Both genders were more sensitive on the lateral aspects of the front torso compared to their respective medial parts (excluding the chest for females). The findings also suggest that females are significantly more sensitive than the males at all lateral aspects of the front torso and at the medial chest. Using the same methods, Ouzzahra et al. (2012) found the lateral aspects of the torso to be more sensitive than the medial aspects to a cold stimulus (20°C). The lateral sites of the front torso can be particularly sensitive to touch and often described as ticklish areas. For TTS_s, when the probe makes initial contact with the skin, it stimulates both thermoreceptors and mechanoreceptors simultaneously. The possibility of a ‘dual’ neural stimulus between mechanoreceptors and thermoreceptors of any region cannot be excluded, particularly in areas such as the lateral torso which may be more sensitive to touch. Few regional differences occurred within the back torso but as with the front, the back was still significantly more sensitive than the extremities. It was evident that the scapula was consistently the least sensitive area for both genders, during rest and exercise and for both TTS_s and SSTS.

Extremities

The majority of locations within the extremities was significantly different to regions within the head. In both genders the legs were the least sensitive areas across the body, which supports findings from the literature on other parameters (Nadel et al. 1973; Nakamura et al., 2008; Stevens et al. 1974; Cotter and Taylor, 2005; Arens et al. 2005). A reduction in the distribution of thermoreceptors towards the extremities will account for the sensitivity differences between the extremities and the torso and head. For the females the upper legs are more sensitive than the lower legs suggesting that sensitivity is in the order of proximal-distal, which is also supported by the head being more sensitive than the torso and the torso more sensitive than the extremities. The opposite is true of the arms and hands as sensitivity increases from the upper arm towards the hands.

The posterior forearm is the least sensitive area within the arm region for both genders. Whether this is related to skin type (i.e. glabrous skin) is a possibility, but requires further investigation. The literature suggests that the hand is densely packed with various types of receptors yet only the females demonstrated a high sensitivity in this area compared to other locations across the body (Jasper and Penfield, 1954; Strughold and Porz, 1931; Rein, 1935, cited in Parsons, 2003, p.59). Females were significantly more sensitive than the males at the anterior forearm, palm and back of the hand. Although using ‘method of limits’ Lautenbacher and Strian (1991) also found that females were more sensitive than males at the hand.

4.4.3 Rest and exercise

It is suggested in the literature that applying a hot stimulus to an individual with a high T_c will result in a different affective thermal sensation to that during conditions with a low T_c; otherwise known as thermal alliesthesia (Cabanac, 1969; Attia and Engel, 1982; Marks and Gonzalez, 1977; Winslow and Herrington, 1949). Research has suggested that this is only relevant for affective thermal sensation (i.e. pleasure/displeasure), but not the intensity of thermal sensation (i.e. hot, neutral of cold) (Mower, 1976). The concept of thermal alliesthesia was originally applicable to individuals exposed to passive heat loads, but Attia and Engel (1982) found it was relevant to exercising individuals with an elevated T_c. However, exercise itself has been reported to cause a reduction in perception to a variety of stimuli, particularly tactile and pain sensitivity (Pertovaara et al. 1984; Kemppainen et al. 1986; Kemppainen et al., 1985; Guieu et al. 1992; Paalasma et al. 1991). This effect is referred to as EIA (exercise induced analgesia) in which neural and hormonal changes occur as a result of exercise (Koltyn, 2000). Ouzzahra et al. (2012) found that during exercise, when T_c was elevated, thermal sensation to a cold stimulus decreased in comparison to at rest, which was associated with EIA.

In the present study, a significant increase in T_c occurred for females but not males. If Cabanac's theory of thermal alliesthesia is applicable to the intensity of a sensation then one would expect a hotter sensation to be reported (for females) yet this was not the case. Exercise significantly reduced magnitude sensation (SSTS) to a hot thermal stimulus in males, but only at select locations for females. Mower (1976) claimed that thermal sensation to a given stimulus is not affected by the thermal state of the body. As no link was found between T_c and thermal sensation, the reduction in magnitude sensation could be a result of EIA. Results from the present study, support the concept of EIA, as thermal sensation was higher at rest than during exercise for both males and females, although female data showed no significant overall effect of exercise. The findings support those of Ouzzahra et al. (2012), who completed a similar investigation as this chapter and they too found that sensitivity to a cold stimulus (20°C) reduced as a result of exercise. It has been reported that exercise causes the release of growth hormones, which in turn reduces the pain thresholds (Kemppainen et al. 1985). Circulating hormones were not monitored in the present study or by Ouzzahra et al. (2012). Future investigations could monitor circulating hormones associated with EIA to see if this is accountable for a reduced sensitivity and determine any gender differences.

As the stimulus was set so not to stimulate noxious heat >42°C, this suggests that EIA is not limited to pain sensitivity but also innocuous thermal sensitivity. Table 4.9 shows the locations across the body that had significant changes in sensitivity from rest to exercise. The males displayed the greatest difference between rest and exercise, which was greatest at the forehead for TTS_S. Despite different methodologies (method of limits), the forehead has frequently been reported as a thermosensitive area (Stevens et al. 1974; Nadel et al. 1973; Cotter and Taylor 2005), which was also found using magnitude estimation in the present study. Interestingly though the results in Table 4.9 suggests that the sensitivity of the forehead is reduced with exercise so that it becomes similar to other sites within the facial area. Areas which displayed no significant differences between rest and exercise generally have a low sensitivity in comparison to other sites, suggesting that EIA is site specific or a given level of sensitivity is required for EIA to have an effect.

4.4.4 Transient and steady state

The duration of the stimulus has a large influence on the sensation experienced and early research by Weber (Ross and Murray, 1996) stated that the initial perceptual responses would be exaggerated and over time the perception of temperature would change, becoming more accurate. In this study, the sign of thermoreceptor overshoot is evident as the raw data for TTS was higher than SSTS. The time difference was 10 seconds, illustrating how quickly the overshoot phenomenon is overcome. It is likely that the larger the temperature gradient the greater the differences between TTS and SSTS and the longer the time required for SSTS to stabilise. However, this was not explored within the realms of this study.

The differences between TTS and SSTS were typically more pronounced for the females (see Table 4.10). In both genders areas within the torso had the largest difference between TTS and SSTS, whilst the extremities had the smallest, particularly the legs. Overall, magnitude sensation of the legs is lower than the remainder of the body and this data suggests that the legs maintain a similar sensitivity regardless of time. It seems then, that less sensitive areas have a lower overshoot on initial contact with a warm stimulus. Despite different methodologies, a number of researchers have also found the extremities, particularly the legs to be an area of low sensitivity (Stevens et al. 1974; Nadel et al. 1973; Nakamura et al., 2008). The front torso was also found to have large differences between TTS and SSTS. The areas within the front torso are very sensitive to touch and often described as ticklish areas. As the probe is in contact with the skin, the stimulation of mechanoreceptors is unavoidable. Therefore, areas particularly sensitive to touch may have a higher sensitivity for TTS than SSTS due to a combined afferent neural stimulation from thermoreceptors and mechanoreceptors which is diminished after the initial contact with the skin. The drop in sensitivity from TTS to SSTS at the lateral and medial abdomen and midaxillary for males is likely to be affected by this.

4.5 Conclusions

Regional thermal sensation to a warm stimulus during rest and exercise was compared between male and females. The differences in transient thermal sensitivity and steady state sensitivity were also investigated. Unless otherwise stated, in the following conclusions, sensitivity includes both TTS_s and SSTS. The following conclusions were drawn.

- Females had a stronger magnitude sensation (SSTS) than males to a warm stimulus (40°C).
- Exercise reduces magnitude sensation to a hot thermal stimulus (40°C) in males but only at select locations for females.
- Sensation magnitude declines with time, which is associated with an overshoot response of the thermoreceptors on initial contact.
- Whilst regional sensitivity was similar across the body for males, the females had several regional differences.
- Sensitivity was greatest at the head, torso and declined towards the extremities. The legs were particularly low sensitive sites in both genders.
- The medial gastrocnemius was the least sensitive for males and the posterior gastrocnemius was the least sensitive for females.
- The cheek had the highest magnitude sensation for the females but not males
- Less sensitive areas showed a lower thermal sensation overshoot on initial contact.
- Sensitivity of the forehead for males was reduced with exercise so that it was similar to other areas within the head region.
- The lateral aspects of the front torso appear to be sensitive areas in both genders, however due to the methodology employed in this study it is possible that a ‘dual’ neural stimulus between mechanoreceptors and thermoreceptors of this region occurred.

Chapter five – Laboratory study 2

The influence of regional skin wettedness on local and whole body thermal comfort and wetness sensation

5 Chapter Summary

The thermal comfort limit has been defined as a whole body skin wettedness value of 0.30 (Gagge et al. 1969a). The purpose of this study was to investigate the influence of local skin wettedness (w_{local}) on local and whole body thermal comfort and wetness sensation during exercise. Six areas of the body were investigated in separate conditions including; chest, abdomen, upper back, lower back, arms and legs. Through manipulating each of the target body areas with a cover of impermeable material, w_{local} was increased above Gagges' comfort limit of 0.3 whilst all other areas across the body were controlled below this comfort limit. Eleven European Caucasian males (age 23.7 ± 2.0 years; height 181.3 ± 6.3 cm; body mass 76.2 ± 11.7kg) walked at 4.5 km·hr^{-1} for 45 minutes in 20.2 ± 0.5°C and 43.5 ± 4.5% RH in each condition. Local thermal comfort and wetness sensation were measured and reported every 5 minutes. Strong correlations existed between local thermal comfort and wetness sensation with w_{local} ($r^2>0.88$, $p<0.05$ and $r^2>0.83$, $p<0.05$, respectively). The thermal comfort limits according to w_{local} of each location were identified (in order of high-low sensitivity); lower back (0.40), upper legs (0.44), lower legs (0.45), abdomen (0.45), chest (0.55), upper back (0.56), upper arms (0.57) and lower arms (0.65). Fukazawa and Havenith (2009) found the arms and legs to be the most sensitive, but the present study found the lower back, legs and abdomen are the most sensitive areas whilst the arms are the least sensitive. Results for the (upper) legs may have been confounded by other factors. A strong relationship was found between thermal comfort and wetness sensation ($r^2>0.66$, $p<0.05$). Participants perceive sweat on the skin before it is felt as uncomfortable. The degree of discomfort and wetness sensation experienced during the investigation were just above the threshold and future studies are required to explore situations when discomfort and wetness sensation are high.

5.1 Introduction

In the previous chapter thermal sensation to a hot dry stimulus across the body was investigated. The head region was evidently a highly sensitive area and the legs the least. These findings correspond with the distribution of thermoreceptors which are densely populated in the head and fewer in the extremities. Factors that influence regional thermal comfort in warm conditions are difficult to ascertain due to a lack of 'comfort' receptors. A large cohort of studies suggests that thermal comfort is driven by whole body skin wettedness (w_{body}) (Gagge et al. 1969a, Nishi and Gagge, 1977; Fukazawa and Havenith, 2009). However, regional variations of temperature sensation and thermal comfort have been identified even in the same environmental conditions (Fukazawa and Havenith, 2009; Cotter et al. 1996). Sweat gland distribution and sweat production also vary across the body and between individuals (Havenith et al. 2008; Smith and Havenith, 2011, 2012). Therefore it is assumed that w_{local} will differ across the body and, as a result, have different influences on local and whole body sensations. It is uncertain whether humans accept higher *w* levels on sites that naturally produce large volumes of sweat. In terms of clothing design, it is possible to assume that more ventilation or sweat absorbing fabrics should be placed where there is a high level of sweat production, but this might not necessarily produce the most comfortable sensations. What will be established from this study are the areas which are sensitive to the build up of sweat and how much sweat local areas can tolerate before they no longer feel comfortable. The aim of this investigation is to determine the influence of local skin wettedness (w_{local}) on local and whole body thermal comfort and wetness sensation.

5.1.1 Previous research

Research on *w* has shown this to be highly correlated with thermal comfort (Gagge et al. 1969a, Nishi and Gagge, 1977; Fukazawa and Havenith, 2009) and it is clear that the presence of moisture is the driving force for discomfort. However, research has failed to link the perceptual response of thermal comfort with the sensation of wetness when measuring w_{local} or w_{body}. Researchers have attempted to find correlations between sudomotor activity (sweat rate, skin wettedness and skin *RH*) and the sensation of sweating/wetness (Nielsen and Endrusick, 1990; Gwosdow et al. 1989). Because of the absence of wet receptors, it is likely that the sensation of sweating/wetness is due to sweat moving along the skin surface; this stimulates tactile receptors and provides feedback regarding the presence of sweat. Toftum et al. (1998) found strong correlations between both the perception of skin humidity and the perception of clothing humidity with skin *RH* (r^2=0.66 and r^2=0.92, respectively). Storaas and Bakkevig (1996) tested 6 males during rest and exercise and found moderate correlations between subjective ratings of wet skin during work and rest with *w* (r^2=0.53 and r^2=0.50, respectively).

Research supporting the idea that *w* contributes to the sensations of wet skin has recently been disputed by Newton et al. (2007) who modified microclimate *RH* whilst maintaining a stable temperature around the torso and measured the perception of skin wettedness. An increase in microclimate *RH* did not cause an alteration in skin wettedness perception but did cause an increase in local T_{sk} which strongly influenced thermal sensation. This was associated with the reduction in heat loss due to the elevations in *RH.* The influence of change in microclimate *RH* on thermal sensation was supported by a later study from the same authors (Newton et al., 2009), who found strong relationship between the perception of microclimate RH and skin temperature change. This supports other authors who suggest the perception of wetness is the effect of evaporative cooling of sweat from the skin surface (Lee et al. 2011; Tiest et al. 2012; Li, 2005). The studies of Newton et al. (2007, 2009) artificially changed the microclimate *RH* via small vessels or air perfused vest over target areas. The mechanisms behind the perception of sweating/wet skin may not only be affected by the *RH* but may also be related to production of sweat from within the skin as it has been suggested that sweating causes swelling of the epidermis which in turn increases receptor sensitivity (Berglund and Cunningham, 1986; Berglund, 1995, cited in Arens and Zhang, 2006, p.595). It is debatable as to whether perceptual responses associated with sweating can be replicated by changing the microclimate. Earlier studies have carried out similar investigations; including Hollies et al. (1979) who found that sensations of sweat normally felt on the skin was replicated by adding 10-20% water to the clothing worn by the participants, proving that skin-fabric interaction was involved in producing sweat sensations. Later, Bentley (1900) found that cold temperature material stimulated the feeling of wetness in the absence of moisture. The cooling mechanism of evaporation is also associated with the sensation of sweating and/or wetness due to the temperature change with evaporative cooling (Wang et al., 2002). However, when T_{sk} increases or is maintained at stable temperatures the influence of evaporative cooling cannot be the determinant for the sensation of wet skin. What drives wetness sensation with increasing T_{sk} remains unanswered. A plethora of research exists determining the link between wet skin and the perception of moisture but, with a lack of moisture sensing receptors, the results have varied. Overall, the studies in this area support the notion that factors influencing the sensations of wet skin are related to either a reduction in T_{sk} due to evaporation, (whether induced by sweat on the skin or by moisture in the clothing) and tactile properties. Alongside this, much of the research aimed to find correlations with physiological parameters but failed to quantify it. Therefore this study will attempt to quantify w_{local} and w_{body} with perceptions of wetness and determine the link between wetness sensation and thermal comfort.

As detailed in the literature review, both Fukazawa and Havenith (2009) and Umbach (1982) conducted investigations concerning the effects of w_{local}, w_{body} and relative humidity (*RH)* on local thermal comfort. The investigations were carried out under the hypothesis that comfort is not determined by w_{body} but by localised areas as a result of varying regional sweat production. In order to carry out this investigation, both studies attempted to increase $\mathrm{w}_{\mathrm{local}}$ in target zones using clothing with different water vapour resistances. Fukazawa and Havenith (2009) increased w_{local} in one area from below the comfort limit (<0.3) to above the comfort limit (>0.3), whilst an attempt was made to keep other areas below the comfort limit (<0.3). From the results the authors were able to establish which of these areas were the most sensitive for thermal comfort due to w_{local}. The arms and legs were reported to be the most sensitive to sweat, with a thermal comfort limit of 0.32 (± 0.07). This was followed by the front torso (0.40 ± 0.11) and then the back torso (0.45 ± 0.18). Whole body thermal comfort was significantly correlated with w_{body} (r^2=0.85, p<0.001) and the comfort limit of the whole body was 0.36. This value is slightly higher than that reported by Gagge et al. (1969a) (0.30) but consistent with the prediction of the thermal comfort limit relative to metabolic rate as proposed by Nishi and Gagge (1977). Umbach (1982) also manipulated body sites with impermeable material and despite some slight differences in methodology; he reported similar findings to Fukazawa and Havenith (2009) with the chest and back tolerating higher levels of w_{local} than the extremities. Umbach's main focus was upon the influence of *RH* on local sensations but he did convert his findings into w_{local} and w_{body}. He claimed that the microclimate *RH* in the lower leg must remain below 46% (w_{local} of 0.10) to be perceived as comfortable whilst the chest was 75% (w_{local} of 0.42). He also found whole body wear comfort was achieved with a skin wettedness of <0.32, this was found to be highly correlated to overall wear comfort (r^2=0.98) and regional differences were observed. Regional differences and a comparison of data to Fukazawa and Havenith (2009) are presented in Table 5.1.

Table 5.1 shows some similarity between the studies and w_{body} comfort limits are consistent with previous literature, yet w_{local} is relatively new to this research area and an in-depth look suggests that the results are not straightforward. The main problem can be explained from Figure 5.1 (taken from Fukazawa and Havenith, 2009), which illustrates significant differences in w_{local} at the four target locations. They concluded that the arms and thighs have a higher thermal sensitivity to w_{local} than the front and back.

Table 5.1: A comparison of the local thermal comfort limits of different body sites to w_{local} (i.e. the threshold for when each body site is considered to be uncomfortable), according to Umbach, (1982) and Fukazawa and Havenith (2009). * indicate where the back included the buttocks and the chest included the front torso and groin area in Fukazawa and Havenith (2009).

Regional zones	Umbach (1982)	Fukazawa and Havenith (2009)
Whole body	0.30	0.36
Chest*	0.42	0.40
Back*	0.49	0.45
Arms	0.32	0.32
Upper leg	0.41	0.32
Lower leg	0.10	-

From Figure 5.1 marked contrasts at the front and back can be observed when they were the target and non-target zones as the authors planned. This contrast in w_{local} is however substantially less for the extremities, particularly the arms when it was covered in impermeable material and when it was not. For example, during test type C (arms, indicated by ■) it is questionable if thermal comfort was indeed influenced solely by the arms as planned as the w_{local} at the front and back was only slightly lower than the arms (0.35, 0.36 and 0.41, respectively). The findings for the extremities may have been confounded by the relatively high w_{local} values at the torso. Unfortunately Umbach (1982) does not report the RH, water vapour pressure or w_{local} for the non-target areas. The main reason as to why Fukazawa and Havenith (2009) were not able to create a clear difference between these zones may be found in the substantially higher levels of sweat production at the torso compared to the extremities (Smith and Havenith, 2011, 2012) making it virtually impossible to markedly increase w_{local} in the arms and legs above that of the rest of the body with the technique used. Further still, the test garment used by Fukazawa and Havenith (2009) had low permeable material covering target zones (intrinsic local thermal resistance 0.15 $m^2 \cdot K \cdot W^{-1}$ and intrinsic local water vapour resistance 62 $m^2 \cdot Pa \cdot W^{-1}$), but this was only placed over the clothing and nothing prevented the airflow underneath the clothing between areas to transfer to the nearby skin surface thus limiting the build up of w_{local} especially in the low sweat zones.

Hence there is some uncertainty as to whether the w_{local} at the non-target zones was kept below the comfort limit in all cases. Therefore the purpose of this investigation is to replicate the experiment outlined by Fukazawa and Havenith (2009) with alterations to the methodology that should increase the contrast between zones, with the goal to determine whether the extremities are actually more sensitive than the torso and confirm local thermal comfort limits. Additionally the experiment will investigate the relationship between local thermal comfort, the perception of wetness and w_{local} in more localised zones as previous investigations have demonstrated substantial regional sweat distributions within the torso (Havenith et al. 2008; Machado-Moreira et al. 2008). Fukazawa and Havenith (2009) investigated the front and back torso however the chest and abdomen have been shown to have different sweat rates (Smith and Havenith, 2011), as have the upper and lower back. Therefore these areas will be investigated independently as will the arms and legs. In order to achieve this, the target areas will not be of the same surface area. Although research has claimed that surface area will influence perceptual responses, understanding segmental differences in terms of sensitivity was deemed to be more relevant to clothing design.

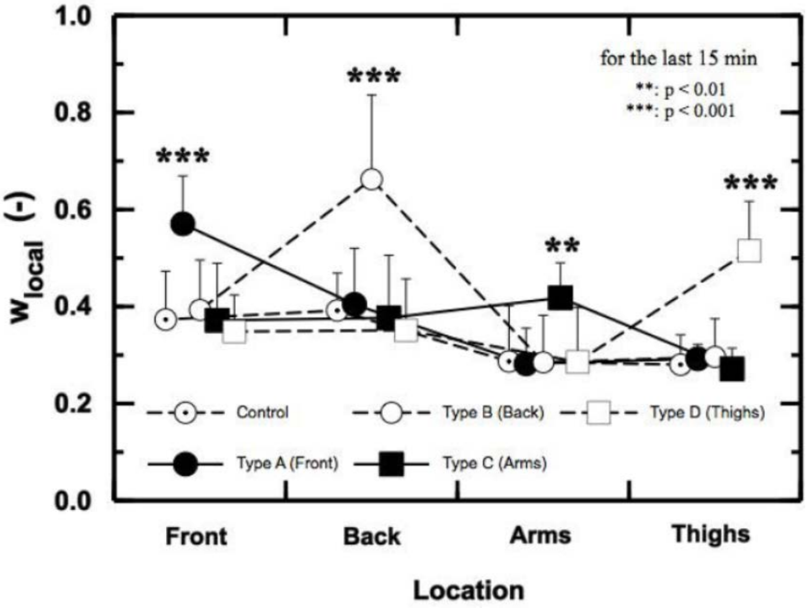


Figure 5.1: Mean local skin wettedness (w_{local}) measured at four locations whilst wearing five different types of garments. The type of garment indicates which area of the body was manipulated to increase local skin wettedness (i.e. type B (Back) (taken from Fukazawa and Havenith, 2009). Asterisks indicates significant differences in w_{local} on the individual target locations, **p<0.01, **p<0.001.

5.1.2 Aims

The aim of this experiment is to determine the influence of w_{local} on local and whole body thermal comfort. Further to this, the study aims to determine the thresholds at which the skin begins to feel wet, locally and across the whole body. This will help establish the extent and duration between when skin is sensed as being wet and when it is perceived as being uncomfortable. Finally, the influence of w_{local} on wetness sensation and the link with thermal comfort will also be addressed.

5.2 Methods

The experimental methodology is outlined in Chapter 3. The pre-test session measuring anthropometrics (skin folds) and submaximal fitness testing was not carried out. A summary with specific details to this experiment will be described here.

5.2.1 Participants

Eleven European Caucasian males (age 23.7 ± 2.0 years; height 181.3 ± 6.3 cm; body mass 76.2 ± 11.7kg) were recruited from the staff and student population at Loughborough University.

5.2.2 Experimental design

The experiment was a repeated measures design with each participant acting as their own control. Local and whole body skin wettedness were simultaneously controlled at a desired level (<0.3 or >0.3) by custom made clothing ensembles, exercise and environmental conditions that were established from pilot tests. Seven garments were designed in order to increase w_{local} at 6 target areas and one control garment. Participants wore each garment during separate trials, separated by at least 2 days and the order of garments was balanced. All experiments were conducted in a temperature controlled room, held at 20.2 ± 0.5°C and 43.5 ± 4.5% RH in the Environmental Ergonomics Research Centre (EERC), Loughborough University, UK.

5.2.3 Clothing

In the following test, six target locations were selected: chest, abdomen, upper back, lower back, arms and legs. As a result seven clothing ensembles were designed, one for each target zone and a control condition. Clothing for all experiments was standardised for each participant and consisted of a 100% polyester long sleeve top and trouser ensemble with a high permeability for heat and vapour transfer with total thermal resistance of 0.154 $m^2 \cdot K \cdot W^{-1}$ and total water vapour resistance 35.9 $m^2 \cdot Pa \cdot W^{-1}$

all tested on a thermal manikin (Newton, Measurement Technology Northwest, USA). For each individual target location the test garment was covered with impermeable material on the respective area to reduce the local vapour permeability. The total thermal resistance and water vapour resistance for each test garment can be viewed in Table 5.2 alongside the surface area. The water vapour resistance for the target locations (>200 m^2 Pa W^{-1}) was higher than the non-target locations (<100 m^2 Pa W^{-1}) and the high values indicated complete impermeability. The average total thermal resistance for each clothing ensemble with impermeable material (excluding the control clothing) was 0.25 ± 0.1 m$^2\cdot$K$\cdot$W^{-1} and the average total water vapour resistance was 40.6 ± 14.8 m$^2\cdot$Pa$\cdot$W^{-1}). The impermeable material was placed over the clothing to ensure that the texture of the clothing next to the skin was uniform across the body, so not to influence tactile receptors. Photographs of the clothing ensembles can be viewed in Figure 5.2a-g. Double sided-tape (1522D, 3M, UK) was attached to the skin and clothing to enclose the microclimate of the target area at the chest, abdomen, upper back and lower back. For the arms and legs an elastic band was used to enclose the target areas at the top of each extremity.

Table 5.2: The percentage surface area (%) of each target location (estimations based on Lee and Choi (2009). The thermal resistance and water vapour resistance of the target area and the total clothing ensemble tested on a thermal manikin (Newton, Measurement Technology Northwest, USA).

Location	Surface Area (%)	Total thermal resistance (m^2 K W^{-1})		Total water vapour resistance (m^2 Pa W^{-1})	
		Target location	Total	Target location	Total
Control	0	N/A	0.154	N/A	35.9
Chest	9%	0.20	0.155	>200	35.4
Abdomen	8.5%	0.35	0.153	>200	33.2
Upper back	6.3%	0.23	0.153	>200	33.5
Lower back	3.1%	0.34	0.161	>200	32.6
Upper arm	8.8%				
Lower arm	6.1%				
Total arms	14.9%	0.16	0.156	>200	38.1
Upper leg	15.3%				
Lower leg	13.6%				
Total Legs	28.9%	0.21	0.165	>200	70.5

Figure 5.2: The clothing ensemble used in each condition. Impermeable material is placed over the target areas (indicated in black) for the following conditions; a) control, b) chest, c) abdomen, d) upper back, e) lower back, f) arms, g) legs.

5.2.4 Methodology

Pre and post-test nude weight was recorded during each condition. Participants self inserted a rectal probe 10 cm beyond the anal sphincter. Following this, each participant dressed in the required clothing ensemble (detailed above). Eight skin thermistors and eight temperature/humidity sensors were attached to the skin at the following locations; chest, abdomen, scapula, lower back, upper arm, forearm, thigh and calf. The temperature/humidity sensors were used to measure w_{local} as outlined in Chapter 3. Once fully equipped the participants rested for 15 minutes in the experimental room (20.2 ± 0.5°C, 43.5 ± 4.5% *RH*) to allow physiological responses to stabilise. During the rest period the participants were familiarised with the sensation scales and allowed to practice. Following the rest period, participants were required to walk at 4.5 km·hr^{-1}, 1% gradient for 45 minutes. All physiological and environmental measurements were recorded at 10 second intervals and 5 minute averages were taken for analysis.

5.2.5 Perceptual responses

Thermal sensation, wetness sensation and thermal comfort were assessed using the scales in Table 5.3. Participants were instructed how to interpret and score them. They scored each sensation for their whole body and each local body region (chest, abdomen, upper back, lower back, upper arm, lower arm, upper legs and lower legs) during the last 5 minutes of rest and at 5 minute intervals during exercise.

5.2.5.1 Thermal comfort limit and wetness limit

The thresholds for when the skin no longer felt comfortable or dry was defined as the w_{local} that corresponds with a comfort vote of -1 and wetness vote of 1. These values will be used to define the sensitivity of localised zones to w_{local} and w_{body}. This method is the same as that employed by Fukazawa and Havenith (2009) and Umbach (1982).

5.2.6 Data Analysis

All data in tables and figures are given in terms of mean values and their standard deviation (± SD) for 5-minute periods. Data collected was analysed using repeated measures ANOVA with the zone (i.e. the experimental condition) set as the independent variable and dependent variables set as the physiological responses (T_c, T_{sk}, w_{local} *and* w_{body}) and perceptual responses (thermal sensation, wetness sensation and thermal comfort). Data was analysed over time was using two-way repeated measures ANOVA, studying the relationship between dependent variables in each condition over time. Regression analysis was performed to assess the correlations between the perceptual responses (thermal comfort and wetness sensation) and physiological responses (T_c, T_{sk} and w_{local}). The regression analysis was conducted on whole body and local sites.

Table 5.3: The perceptual scales used in the present study for the assessment of thermal sensation, wetness sensation and thermal comfort.

Thermal sensation	Wetness sensation	Thermal comfort
+10 Extremely hot	0 Dry	0 Comfortable
+9	1	-1
+8 Very hot	2 Moist	-2 Slightly uncomfortable
+7	3	-3
+6 Hot	4 Wet	-4 Uncomfortable
+5	5	-5
+4 Warm	6 Dripping wet	-6 Very uncomfortable
+3		
+2 Slightly Warm		
+1		
0 Neutral		
-1		
-2 Slightly cool		
-3		
-4 Cool		
-5		
-6 Cold		
-7		
-8 Very cold		
-9		
-10 Extremely cold		

5.3 Results

5.3.1 Confirmation of the experimental design

The aim of the experiment was to investigate the influence of w_{local} on local and whole body thermal comfort. This was achieved by exposing participants to 7 conditions, whereby w_{local} of one area was independently increased beyond a theoretical comfort limit (0.30) and local thermal comfort was assessed.

During each condition the ambient conditions were controlled at (a mean ± S.D) 20.1 ± 0.6°C and 43 ± 4.5% RH. Repeated measures ANOVA revealed no significant differences in T_a or RH between conditions (p>0.05). T_c during rest was 37.0 ± 0.1°C for all conditions and was 37.05 ± 0.1°C at the end of the exercise period. Repeated measures ANOVA revealed no significant effect of condition or time for T_c. Gross sweat loss (GSL) was measured for each participant and during each test. Figure 5.4 indicates GSL (corrected for respiratory and metabolic cost) in grams per surface area per hour ($g \cdot m^{-2} \cdot h^{-1}$) for each condition. Due to the large variations of GSL between individuals the median value is also presented as it is less affected by extreme values. Repeated measures ANOVA with post hoc comparisons revealed no significant differences between GSL between each test condition.

Table 5.4: Mean, standard deviation (SD) and median gross sweat loss (GSL) ($g \cdot m^{2} \cdot h^{-1}$), corrected for respiratory and metabolic mass loss for each condition.

Condition	Corrected GSL ($g \cdot m^{2} \cdot h^{-1}$)		
	Mean	SD	Median
Control	67.1	101.1	66.5
Chest	80.3	89.6	95.7
Abdomen	128.0	208.8	101.8
Upper back	101.1	83.2	77.7
Lower Back	96.3	61.8	115.1
Arms	84.3	85.6	68.9
Legs	118.4	97.5	110.0

The average $\bar{T}_{sk}$ over all conditions was 31.35 ± 0.9°C. $\bar{T}_{sk}$ remained relatively stable throughout each condition after a small decrease during the initial onset of exercise. Analysis revealed no significant effect of condition or time on $\bar{T}_{sk}$. Local T_{sk} also remained stable over the course of each condition. The average local T_{sk} over all condition was; chest 31.35 ± 1.2°C, abdomen 31.8 ± 1.2°C, upper back 32.91 ± 0.8°C, lower back 31.9 ± 1.5°C, upper arm 30.1 ± 1.2°C, lower arm 30.8 ± 1.0°C, upper leg 30.8 ± 1.4°C, lower leg 30.8 ± 1.3°C). Local T_{sk} of the target area did not increase as a result of the impermeable material. Three-way repeated measures ANOVA revealed no significant overall effect of condition or time. A significant overall effect of location was found ($p<0.05$) and post hoc analysis revealed the T_{sk} of the lower back was significantly higher than the upper and lower arms ($p<0.05$). The T_{sk} of the upper back was significantly higher than the following sites; upper arm, lower arm, upper leg and lower leg ($p<0.05$).

Figure 5.3 illustrates the variation of w_{body} over time in all test target conditions. In all conditions, as planned, w_{body} started below and ended at or above Gagge’s comfort limit 0.30. Only during the upper back and lower back condition did w_{body} fail to reach a value over 0.30, however this did not prevent participants from no longer feeling ‘comfortable’. The data in Figure 5.3 suggests very little difference between w_{body} for each condition at rest and after 45 minutes of exercise (except the legs). Repeated measures ANOVA revealed a significant effect of condition and time ($p<0.05$) on w_{body}. Post hoc analysis revealed that at 45 minutes w_{body} was significantly higher ($p<0.05$) during the leg condition compared to the following conditions; control, chest, abdomen, upper back and lower back.

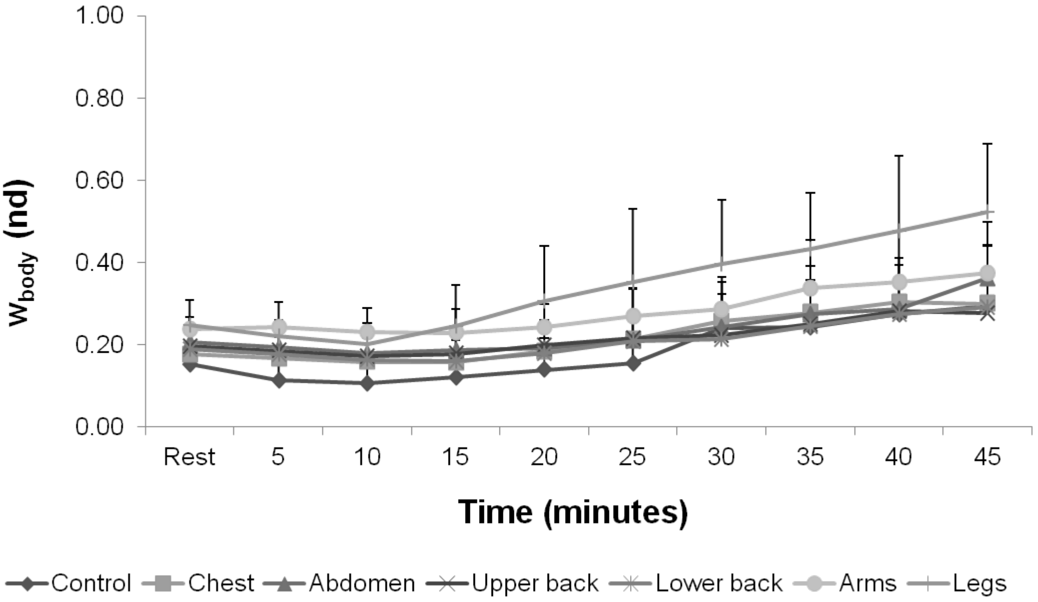


Figure 5.3: Males (n=11) mean (±SD) w_{body} over time during each test condition (i.e. when each body site was manipulated).

w_{local} of the target site in each condition increased over the time period of each test (see Figure 5.4). Repeated measures ANOVA revealed that the effect of location was not significant ($p>0.05$). Paired samples t-test was performed on w_{local} for the target area in each condition between rest and 45 minutes. Results revealed a significant increase ($p<0.05$) in w_{local} at all sites except the upper back during the upper back condition and upper legs during the leg condition.

The clothing ensemble was designed to increase w_{local} in the target location above the comfort limit whilst maintaining a low w_{local} in non-target locations. Figure 5.5 illustrates mean w_{local} and w_{body} during the last 15 minutes of each test condition. Typically, one peak occurs per line which corresponds to the body part which was the target location.

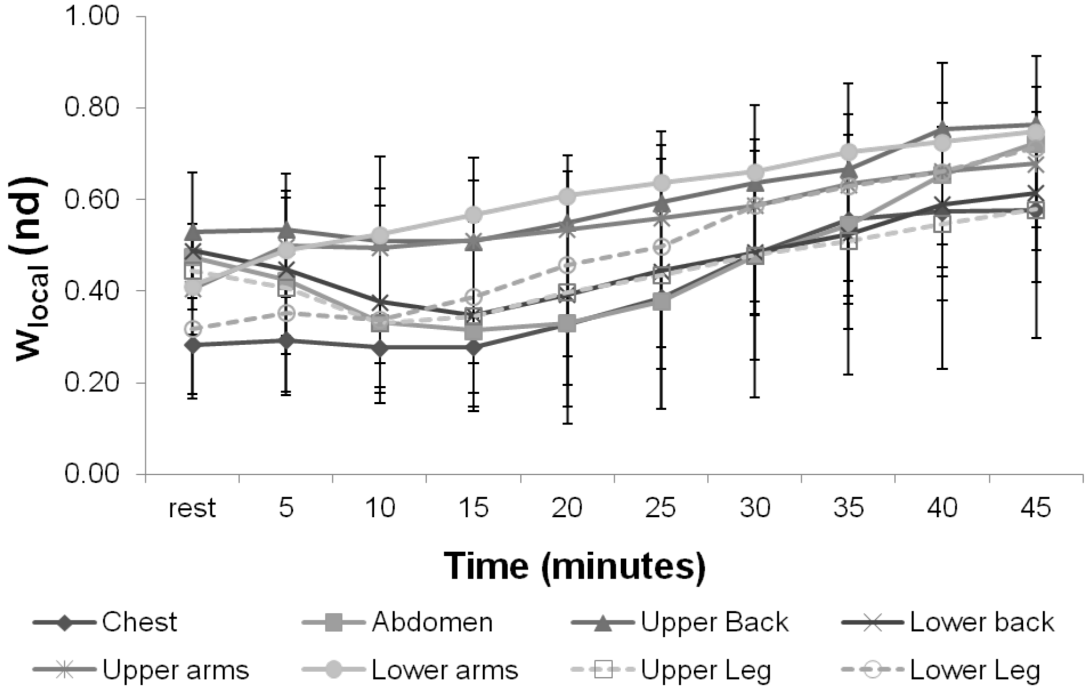


Figure 5.4: Males (n=11) mean (±SD) w_{local} of the target areas only during each respective condition (i.e. w_{local} of the chest is displayed during the chest condition).

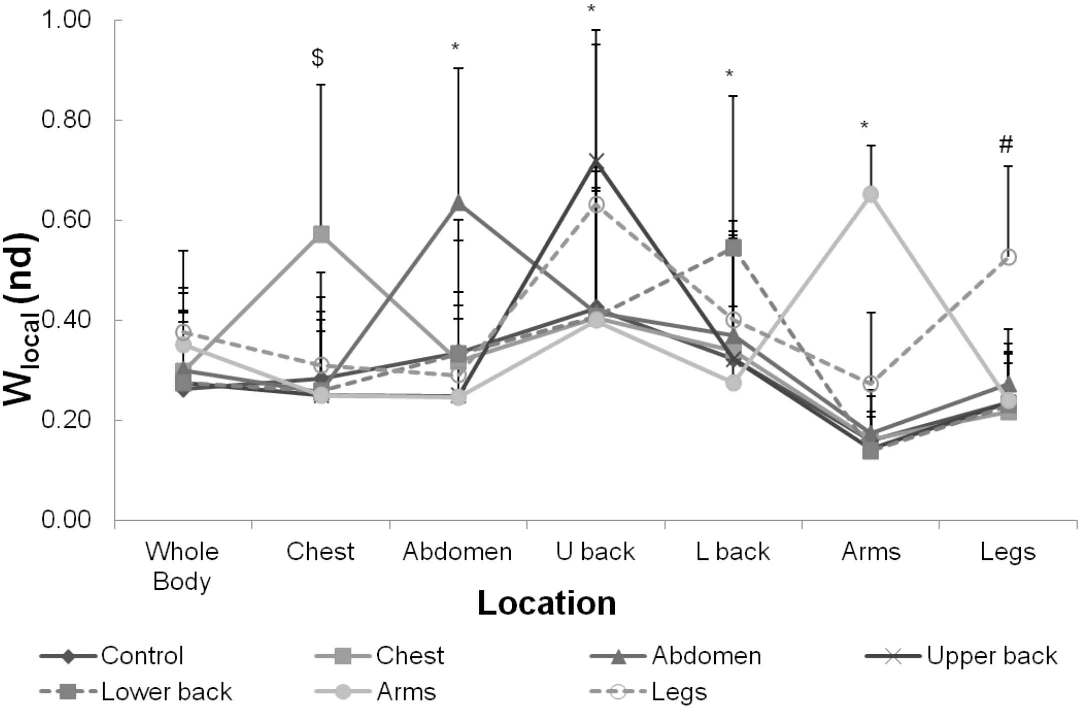


Figure 5.5: Males (n=11) mean w_{local} from the last 5 minutes of exercise at each location whilst wearing different types of garments). The garment type is illustrated in the legend (representing each test condition). * indicates significant difference to all other locations in the same test. # indicates significant difference to all locations except the upper back, $ significant difference to all locations except the upper and lower back ($p<0.05$).

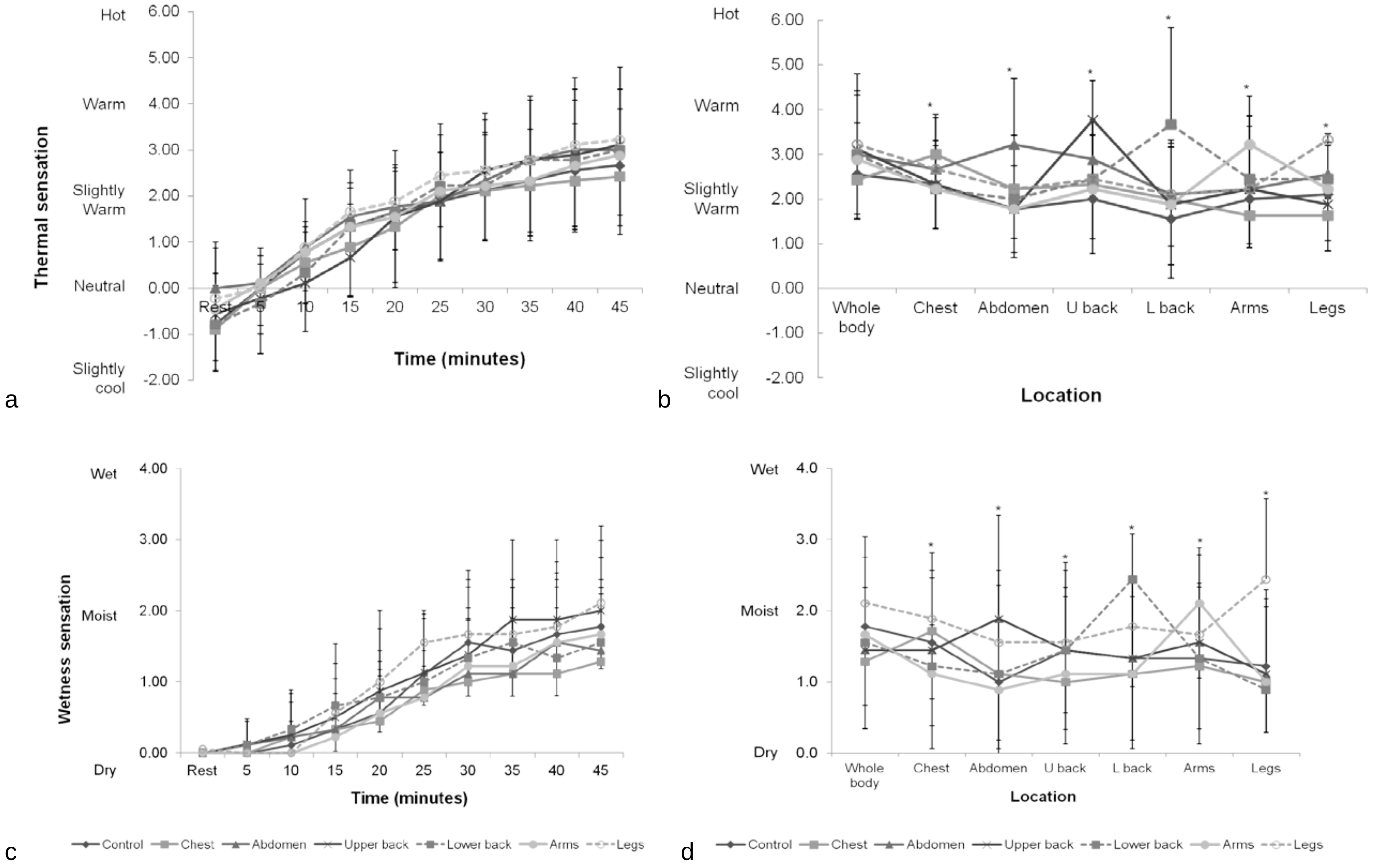
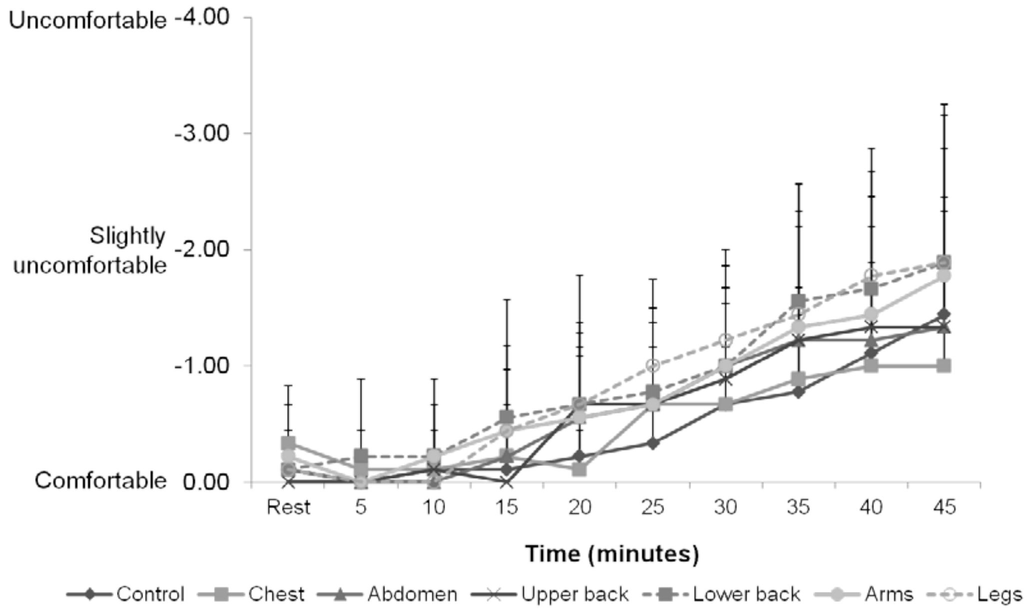


Figure 5.6: a) Whole body thermal sensation and c) whole body wetness sensation during each condition over time; b) Local thermal sensation and d) local wetness sensation (respectively) of the target areas at the end of exercise during each condition. * indicate significant difference between target and non target locations for each condition (p<0.05).



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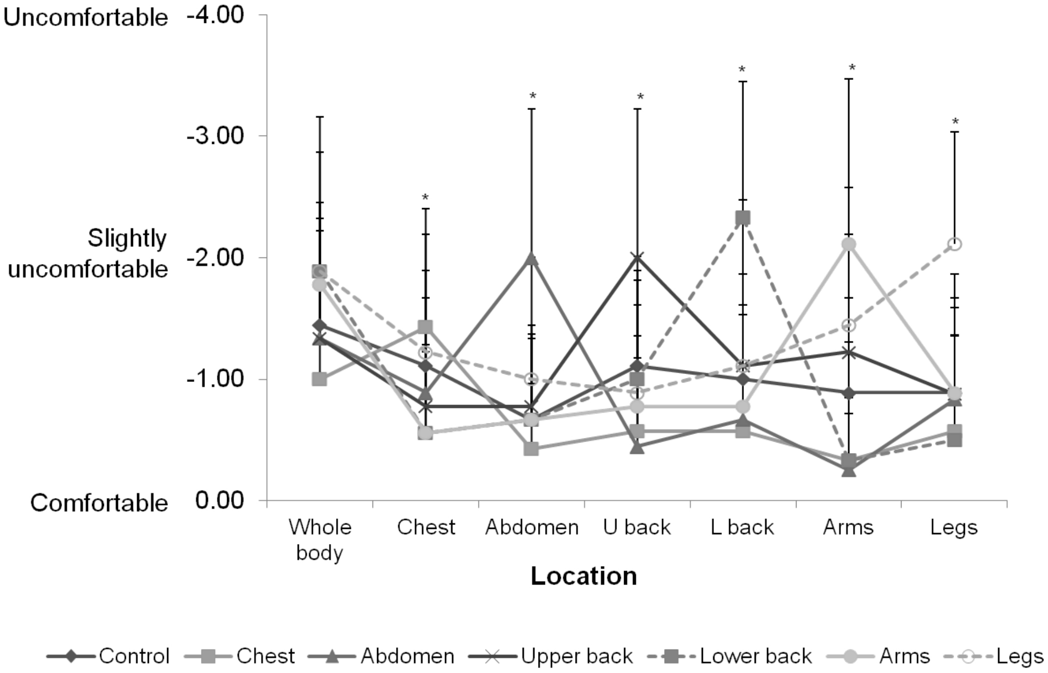


b

Figure 5.7: a) Whole body thermal comfort during each condition over time; b) Local thermal comfort of the target areas at the end of exercise during each condition. * indicate significant difference between target and non-target locations for each condition ($p<0.05$).

There was one occasion whereby the w_{local} of a non-target location was higher than the comfort limit (0.3), which occurred at the upper back during the leg condition. The results from the one-way ANOVA indicate that the w_{local} during each condition was significantly higher at the target area than non-target areas ($p<0.05$). The exception to this rule was during the chest condition, w_{local} at the lower back and upper back was not significantly different from the target area and during the leg condition, w_{local} at the upper back was not significantly different ($p>0.05$).

Main findings:

- all physiological and perceptual responses were similar between conditions;
- clear contrasts were created between w_{local} of the target and non target areas, except during the leg condition.

5.3.2 Perceptual measurements

Whole body thermal sensation and wetness sensation during each condition are plotted against time in Figure 5.6a and c and thermal comfort is plotted in Figure 5.7a-b respectively. Note that the y-axis on each graph covers only a small range of the scales to allow for a clearer representation of the data. By the end of each condition, thermal sensation is slightly warm, whilst wetness sensation is moist and thermal comfort is slightly uncomfortable. Only small variations existed between conditions for each whole body perceptual response and repeated measures ANOVA revealed no significant effect of condition or location but a significant effect of time due to the increase from baseline to the end of exercise ($p<0.05$). Figure 5.6, b and d and Figure 5.7b illustrates the mean perceptual responses for local thermal sensation, wetness sensation and thermal comfort (respectively) scored at the end of each condition for each location. As with w_{local} there is one peak per condition, indicating that each perceptual response was higher for the target area than the other non-target areas. According to repeated measures ANOVA local thermal sensation, wetness sensation and thermal comfort were significantly higher for all the target areas compared to the non-target areas for each condition ($p<0.001$), including the legs.

Main findings:

- all perceptual responses of the target locations were significantly higher compared to non-target locations.

5.3.3 The relationship between perceptual and physiological responses

5.3.3.1 Thermal comfort skin wettedness

The relationship between local and whole body thermal comfort and w_{local} and w_{body} for the target areas for each condition was assessed using Pearson's correlation. Results revealed significant high correlation between whole body thermal comfort and w_{body} during the control condition ($r^2=0.95$, $p<0.05$). Data of whole body thermal comfort and

w_{body} was grouped together for all test conditions and correlation analysis revealed a moderate, significant relationship ($r^2 = 0.66$, $p<0.05$) (Figure 5.8).

Based on these results the comfort limit for w_{body} occurs at 0.30 and whole body thermal comfort can be predicted using the following equation:

$$\text{Whole body thermal comfort} = 0.66 + (w_{body} * -0.55)$$

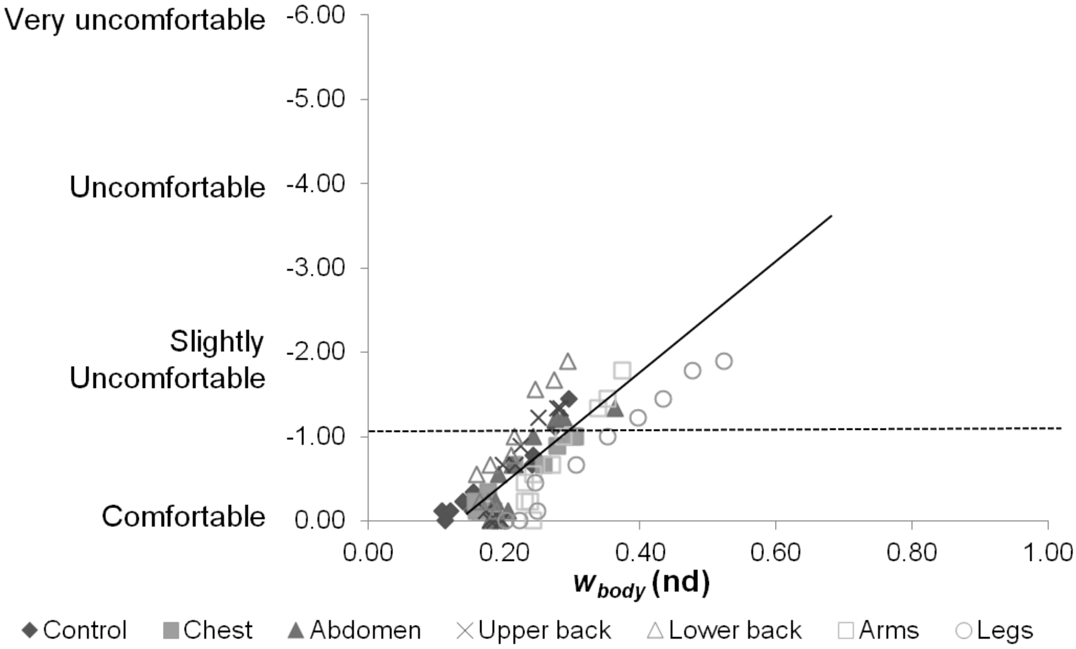


Figure 5.8: Relationship between whole body thermal comfort and w_{body} during each test condition. The dashed line indicates the defined thermal comfort limit (-1 on the y axis). The comfort limit is then taken from the x axis (w_{body}) where the lines cross.

All w_{local} data from each condition was entered into a multiple regression analysis using the stepwise method to predict whole body thermal comfort. According to the results the following equation can be used to predict whole body thermal comfort based on w_{local}:

$$\text{Whole body thermal comfort} = 0.92 + (w_{lower\ back} * -2.27) + (w_{upper\ back} * -1.23) + (w_{lower\ arm} * -1.17) + (w_{abdomen} * -0.73) + (w_{chest} * -0.64)$$

The relationships between local thermal comfort and w_{local} are illustrated in Figure 5.9 (a-d). Values at a comfort score of 0.0 were removed prior to analysis. Correlation analysis for w_{local} and local thermal comfort revealed high, significant correlations at all locations ($r^2>0.88$) (see Table 5.5). In order to determine the influence of w_{local} on whole body thermal comfort, the same analysis was carried out and results also showed high significant correlations ($r^2>0.70$). As w_{local} increased, local and whole body thermal comfort decreased but the point at which each location becomes no longer comfortable (-1 category vote) occurred differently for each location. From Figure 5.9 (a-d) it is possible to identify the local thermal comfort limit (w_{local} that corresponds to a category -1 vote on the comfort scale) of each zone.

Table 5.5 shows local and whole body thermal comfort limit and the lower the comfort limit the more sensitive the area is to w_{local}. The values indicate that the lower back, upper legs and lower legs are the most sensitive zone, followed by the abdomen. The lower arm followed by the upper back and chest are the least sensitive areas. Slight differences are observed between upper and lower legs, yet there appears to be a large difference between the upper and lower arms. Local and whole body thermal comfort can be determined using the regression equations indicated in Table 5.5. The high, significant correlations observed from the data analysis reveal that these equations are valid for conditions employed by this experiment.

Table 5.5: Local and whole body thermal comfort limits and the regression equations for the prediction of whole body and local thermal comfort for each location.

	Local thermal comfort				**Whole body thermal comfort**			
	Thermal Comfort limit	a	b	R^2	Thermal Comfort limit	a	b	R^2
Whole body	-	-	-	-	0.30	0.71	-5.21	0.66
Chest	0.55	0.89	-3.38	0.90*	0.65	0.50	-2.23	0.90*
Abdomen	0.45	0.60	-3.09	0.91*	0.63	0.57	-2.55	0.87*
Upper back	0.56	1.83	-4.80	0.98*	0.65	1.85	-4.04	0.92*
Lower back	0.40	1.21	-5.17	0.90*	0.46	1.38	-4.90	0.86*
Upper arms	0.57	3.08	-7.10	0.93*	0.63	2.27	-5.23	0.84*
Lower arms	0.65	2.21	-4.89	0.92*	0.72	1.64	-3.73	0.83*
Upper legs	0.44	2.02	-7.02	0.88*	0.44	2.32	-7.02	0.72*
Lower legs	0.45	1.85	-6.02	0.98*	0.55	1.50	-4.72	0.98*

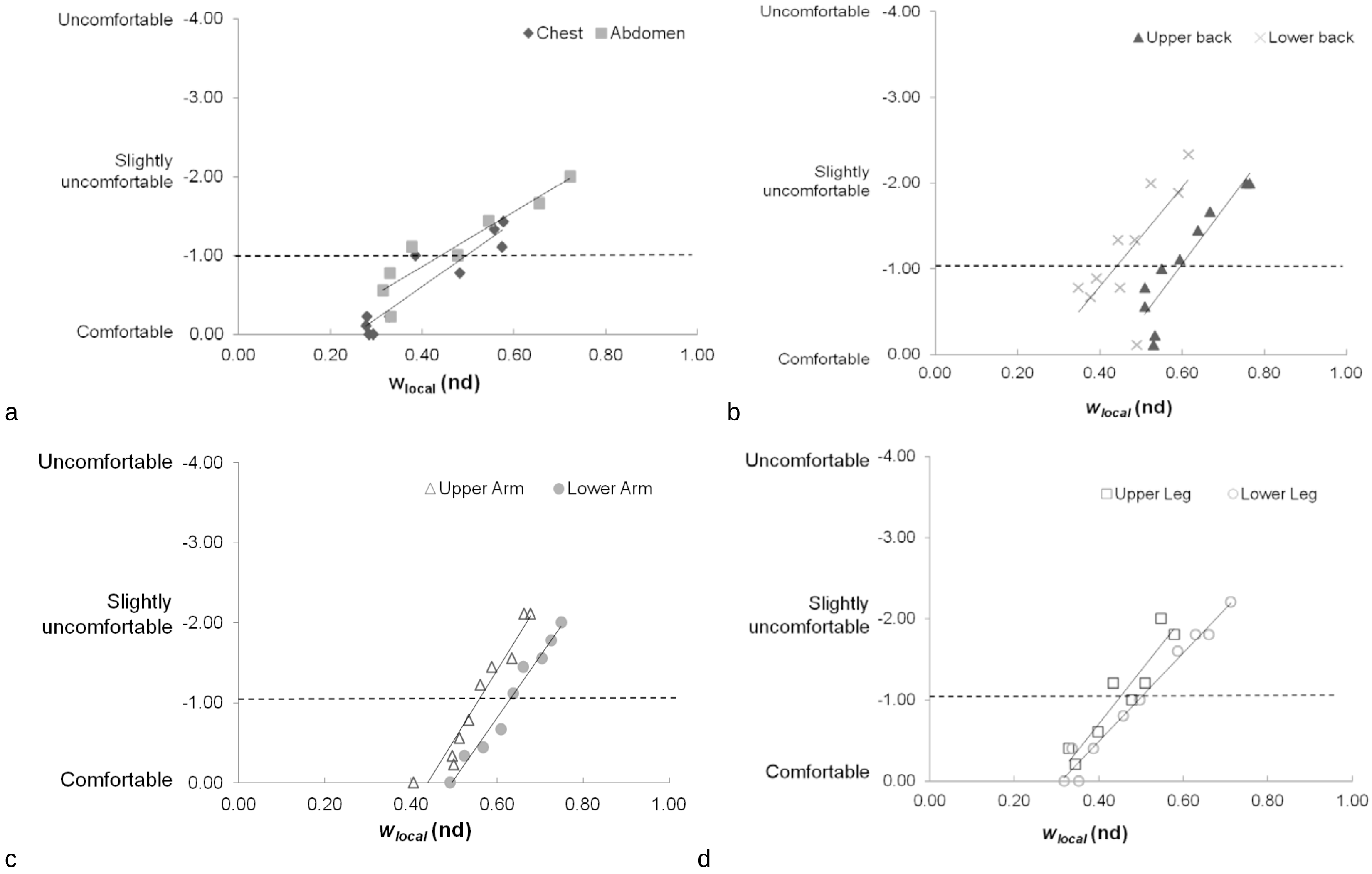


Figure 5.9: The relationship between local thermal comfort and w_{local} at a) chest and abdomen, b) upper and lower back, c) upper and lower arm, d) upper and lower legs. The dashed line indicates the defined thermal comfort limit (-1 on the y axis). The comfort limit is then taken from the x axis (w_{local}) where the lines cross.

Main findings:

- thermal comfort was strongly correlated with w_{local} and w_{body} ($r^2 > 0.88$, $p < 0.05$);
- the thresholds for when the skin no longer feels comfortable was defined as the w_{local} that corresponds with a comfort vote of -1 and the comfort limit of the whole body was 0.30;
- the thermal comfort limits according to w_{local} of each location were identified (in order of high-low sensitivity); lower back (0.40), upper legs (0.44), lower legs (0.45), abdomen (0.45), chest (0.55), upper back (0.56), upper arms (0.57) and lower arms (0.65).

5.3.3.2 Wetness sensation and skin wettedness

The relationship between local and whole body wetness sensation and w_{local} and w_{body} for the target areas for each condition was assessed using Pearson's correlation. Values with a wetness score of 0.0 were removed prior to analysis. Results revealed significant high correlation between whole body wetness sensation and $\mathrm{w}_{\mathrm{body}}$ during the control condition ($r^2=0.88$, $p<0.05$). Data of wetness sensation and $\mathrm{w}_{\mathrm{body}}$ was grouped together for all test conditions and correlation analysis revealed a moderate, significant relationship ($r^2= 0.51$, $p<0.05$) (Figure 5.10).

Based on these results the wetness limit for $\mathrm{w}_{\mathrm{body}}$ occurs at 0.30 and can be predicted using the following equation:

$$\text{whole body wetness sensation} = -0.56 + (w_{body} * 5.81)$$

The relationships between local wetness sensation and w_{local} are illustrated in Figure 5.11 (a-d) and the results from correlation analysis are presented in Table 5.6. Correlation analysis for $\mathrm{w}_{\mathrm{local}}$ and local wetness sensation revealed high, significant correlations at all locations ($r^2>0.83$). Local wetness sensation increases as local skin wettedness increases but as with thermal comfort, the point at which each location becomes no longer dry (-1 category vote) occurs differently for each location. Using Figure 5.11 (a-d), it is possible to identify the wetness sensation limit (w_{local} that corresponds to a category 1 vote on the comfort scale) of each zone in terms of w.

Table 5.6 reveals the local and whole body wetness limit of w_{local} and the lower the value the more sensitive the area is to w_{local}. Lower wetness limits indicate areas which can detect moisture on the skin surface earlier. The values indicate that the abdomen, chest, lower back and upper legs are the most sensitive zones. The upper and lower arms are the least sensitive areas, followed by the upper back. Slight differences are observed between upper and lower legs, yet there appears to be a larger difference between the upper and lower arms. Higher local wetness limits are observed for whole body wetness sensation which is tenable as it requires more sweat on one local site before it will influence the whole body. Local and whole body wetness sensation can be determined using the regression equations indicated in Table 5.6. The high, significant correlations observed from the data analysis reveal that these equations are valid for conditions employed by this experiment.

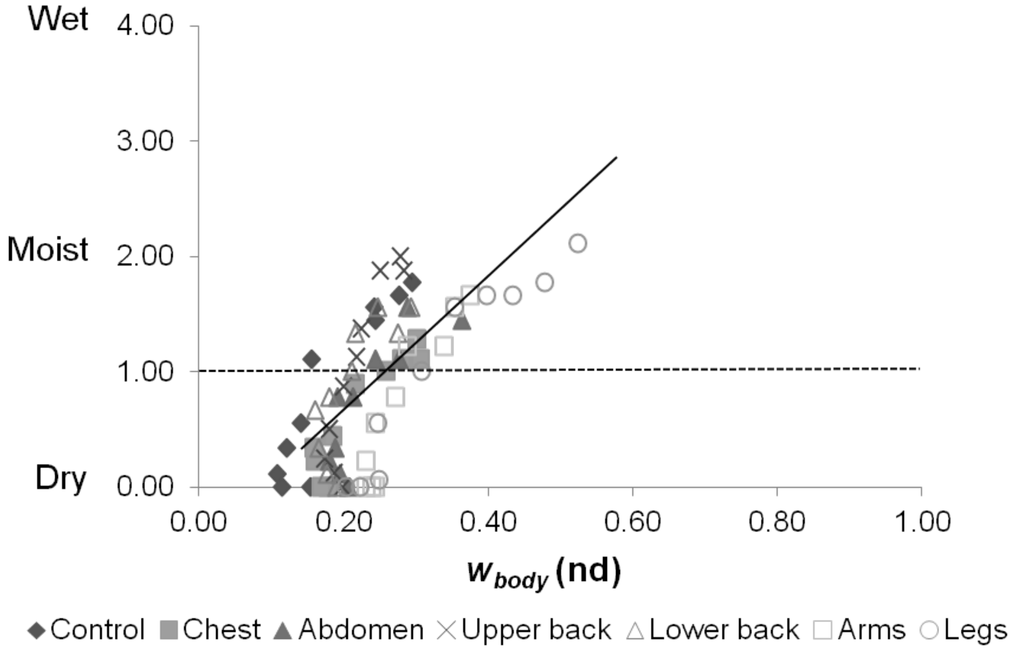


Figure 5.10: Relationship between whole body wetness sensation and w_{body} during each test condition. The dashed line indicates the defined wetness limit (-1 on the y axis). The wetness limit is then taken from the x axis (w_{body}) where the lines cross.

Main findings:

- wetness sensation was strongly correlated with w_{local} and w_{body} ($r^2>0.88$, $p<0.05$);
- the thresholds for the skin no longer felt dry was defined as the w_{local} that corresponds with a wetness vote of -1 and the wetness limit of the whole body was 0.30;
- the wetness limits according to w_{local} of each location were identified (in order of high-low sensitivity); abdomen (0.34), upper legs (0.35), lower back (0.36), chest (0.40), lower legs (0.45), upper back (0.49), upper arms (0.52) and lower arms (0.62).

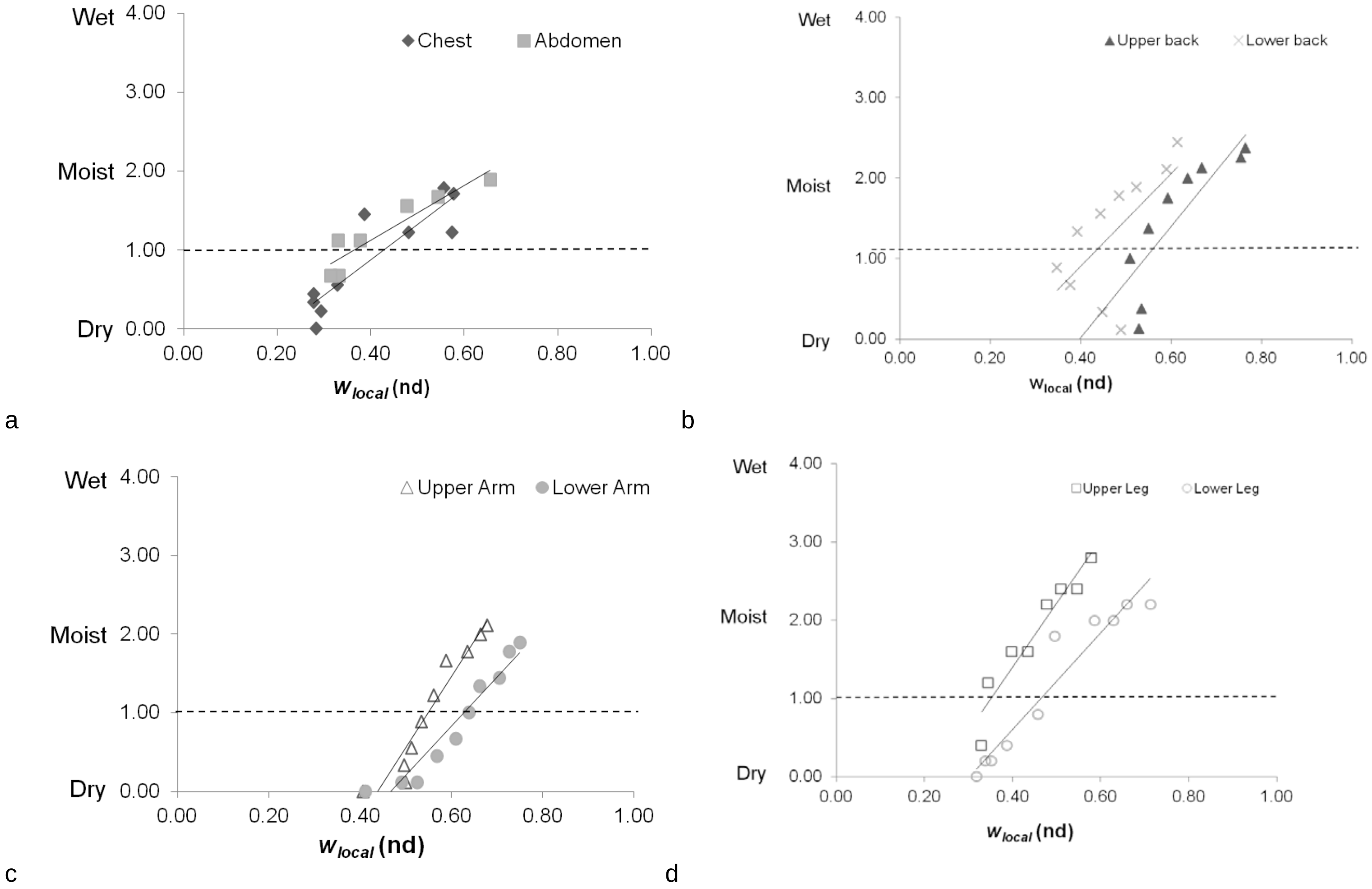


Figure 5.11: The relationship between local wetness sensation and w_{local} at a) chest and abdomen, b) upper and lower back, c) upper and lower arm, d) upper and lower legs. The dashed line indicates the defined thermal comfort limit (-1 on the y axis). The comfort limit is then taken from the x axis (w_{body}) where the lines cross.

Table 5.6: Local and whole body wetness sensation limits and the regression equations for the prediction of wetness sensation for each location.

	Local wetness sensation				**Whole body wetness sensation**			
	Wetness sensation limit	a	b	R^2	Wetness sensation limit	a	b	R^2
Whole body	0.30	-0.56	5.81	-	-	-0.86	8.41	
Chest	0.40	-0.96	4.36	0.83*	0.50	-0.83	3.55	0.89*
Abdomen	0.34	-0.45	3.10	0.95*	0.50	-0.53	2.77	0.91*
Upper back	0.49	-1.25	4.58	0.94*	0.57	-2.20	5.34	0.91*
Lower back	0.36	-1.14	5.50	0.93*	0.57	-0.94	4.09	0.85*
Upper arms	0.52	-3.25	7.72	0.92*	0.60	-2.90	6.45	0.92*
Lower arms	0.62	-2.15	4.83	0.90*	0.65	-2.15	4.63	0.90*
Upper legs	0.35	-1.95	8.63	0.89*	0.45	-1.84	7.12	0.84*
Lower legs	0.45	-2.02	6.77	0.91	0.70	-1.61	5.58	0.91*

5.3.4 The relationship between perceptual responses

Figure 5.12 illustrates the relationship between whole body and local thermal comfort. This indicates that each area when manipulated had a similar influence on whole body thermal comfort. Regression analysis was performed on local thermal comfort for the targeted area and whole body thermal comfort. Results revealed significant high correlations for whole body thermal comfort and all local comfort (r^2=>0.90, $p<0.05$) during all test conditions.

Figure 5.13 illustrates the linear relationship between local thermal comfort and local wetness sensation. According to correlation analysis there is a significant moderate correlation between thermal comfort and wetness sensation of the target locations ($r^2>0.66$, $p<0.01$).

Table 5.7 displays the local and whole body wetness and comfort limits and some locations reach a comfort vote of -1 at the same point as they reach a wetness sensation vote of 1. However at the upper legs, upper back and chest there is a shift in the relationship towards the right, indicating that these areas detect moisture earlier than they perceive it as no longer comfortable.

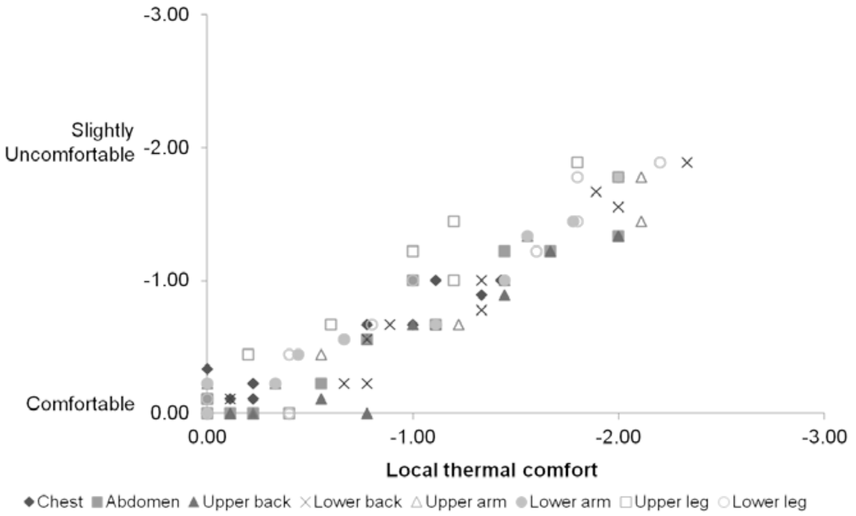


Figure 5.12: The relationship between whole body thermal comfort and local thermal comfort for individual target locations.

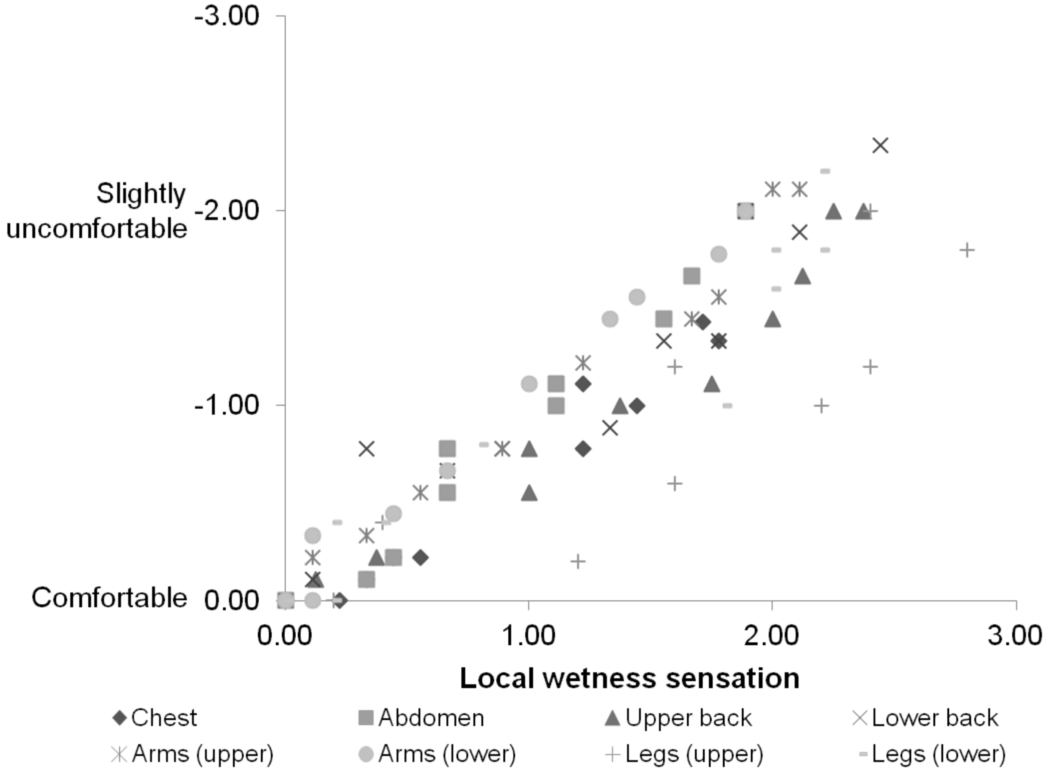


Figure 5.13: The relationship between local wetness sensation and local thermal comfort for individual target locations.

Table 5.7: The local and whole body wetness sensation limit and thermal comfort limit according to w_{body} and w_{local}.

	Local sensation		**Whole body sensation**	
	Wetness sensation limit	Thermal comfort limit	Wetness sensation limit	Thermal comfort limit
Whole body	-	-	0.30	0.30
Chest	0.40	0.55	0.50	0.65
Abdomen	0.34	0.45	0.50	0.63
Upper back	0.49	0.56	0.57	0.65
Lower back	0.36	0.40	0.57	0.46
Upper arms	0.52	0.57	0.60	0.63
Lower arms	0.62	0.65	0.65	0.72
Upper legs	0.35	0.44	0.45	0.44
Lower legs	0.45	0.45	0.70	0.55

Main findings:

- moderate-strong linear relationship exists between thermal comfort and wetness sensation ($r^2>0.66$, $p<0.05$);
- local wetness limits were lower than local comfort limits indicating that participants perceived moisture before they found it uncomfortable.

5.4 Discussion

5.4.1 Experimental Design

The aims of this study were to determine the influence of w_{local} on local and whole body thermal comfort and wetness sensation. In order to achieve these aims the study replicated that of Fukazawa and Havenith (2009) with some alterations in the methodology in order to produce more distinct differences in w_{local} between the target and non target areas. The main difference between trials was the clothing used and the surface area of the target locations. Fukazawa and Havenith (2009) tested 4 locations; front torso, back torso, arms and upper legs. In the present study the front torso was separated into the chest and abdomen and the back torso was separated into upper back and lower back. The arms and legs were inclusive of the whole area. This meant that each target area differed in surface area, resulting in a higher total intrinsic water vapour resistance for the arm and leg condition in comparison to the torso conditions (see Table 5.2). This helped accentuate the contrasts in w_{local} between the torso and extremities.

Table 5.8: A comparison of the local thermal comfort limits, in relation to w_{local} of the target areas, for the present study, Fukazawa and Havenith (2009) and Umbach (1982).

Target Area	w_{local} (present study)	w_{local} (Fukazawa and Havenith, 2009)	w_{local} Umbach (1982)
Chest	0.55	0.56 ± 0.10	0.42
Abdomen	0.45		No data
Upper back	0.56	0.65 ± 0.17	0.49
Lower back	0.40		
Upper arms	0.57	0.40 ± 0.08	0.32
Lower arms	0.65		
Upper legs	0.44	0.50 ± 0.11	0.41
Lower legs	0.45		0.10

The impermeable material had an immediate effect on w_{local} as the target areas at rest were all higher than the non-target areas for each condition; fortunately this did not influence local thermal comfort as all votes began at a ‘comfortable’ state. The combination of exercise and clothing design has the desired effect on w_{local} of the target area as can be seen in Figure 5.5, which illustrates one peak per area (the target area), with the exception of the upper back having a second peak for the leg condition even though this did not affect local thermal comfort of the legs (Figure 5.7b). The results from the one-way ANOVA indicate that the w_{local} during each condition was significantly higher at the target area than non-target areas (all $p<0.05$). In comparison to Fukazawa and Havenith (2009) the w_{local} of the target areas was generally higher (see Table 5.8), but more importantly the contrast between the target and non-target areas was greater, confirming the ability of the clothing to further increase w_{local}, particularly at the limbs. Hence, we can conclude that the aim of improving Fukazawa and Havenith’s study by increasing the contrasts between zones was achieved. During the leg condition, w_{local} of the legs and upper back were both high, whilst all other areas were low. However, local thermal comfort and local wetness sensation were significantly higher at the legs than the upper back. Therefore, data from the leg condition may be used to define the local thermal comfort limits of the legs. However, predicting the influence of the legs w_{local} on whole body thermal comfort should be used with caution as the result may be confounded by the high w_{local} of the upper back.

Repeated measures ANOVA revealed no significant effect of location on the target area w_{local} at the end of exercise confirming that the clothing had a similar effect on each location. This is also confirmed by the stable and no significant changes in T_c , T_b , GSL, $\bar{T}_{sk}$ and local T_{sk} within and between experiments.

5.4.4 The relationship between physiological and perceptual responses

5.4.4.1 Whole body thermal comfort and w_{body}

Research has established the influence of *w* on thermal comfort (Gagge et al. 1969a, Nishi and Gagge, 1977) and more recently Fukazawa and Havenith (2009) were able to identify the influence of w_{local} on local and whole body thermal comfort. The results in this study support these findings as strong correlations between local and whole body thermal comfort with w_{body}, w_{local} were found. Correlation analysis revealed a moderate relationship between whole body thermal comfort and w_{body} (r^2= 0.66, $p<0.05$). The comfort limit of the whole body, which was defined as the *w* that corresponded with the point at which the individual (or location) becomes no longer comfortable (-1 category vote) occurred at 0.30. This is concurrent with the thermal comfort limit proposed by Gagge et al. (1969a) at rest. Fukazawa and Havenith's (2009) found a comfort limit of 0.36, which they claim coincided with Nishi and Gagge's (1977) calculation of *w* based of metabolic rate. It is surprising that similar values were not obtained for this study as estimated metabolic rate was the same. The lower whole body comfort limit suggests that participants were more sensitive but several factors may account for these differences. Fukazawa and Havenith (2009) estimated w_{body} based on 4 locations whereas this study was based on 8 locations which coincides with that used by Umbach (1982) who found a similar whole body comfort limit of 0.32. The most important difference which may account for the discrepancies are the comfort scales used. The present study employed a unipolar comfort scale ranging from comfortable to very uncomfortable. Fukazawa and Havenith (2009) used a bipolar comfort score ranging from 'very comfortable' to 'very uncomfortable' and the comfort limit was defined as the *w* value that corresponds to the transition from 'slightly comfortable' to 'slightly uncomfortable' at the 'neutral' point (0). The comfort limit of the present study was defined as the w_{local} that corresponds to a comfort vote of -1, which is the transition from 'comfortable' to 'slightly uncomfortable' through the midpoint. From Figure 5.14, the difference from comfortable to slightly uncomfortable is much larger than that used by the present study. Depending on how you interpret the 'neutral' vote in the scale used by Fukazawa and Havenith (2009), a difference of one to two category scores exists for the 'comfort limit' between this study and that of Fukazawa and Havenith (2009). The definition of the comfort limit in this study was when the participant no longer felt comfortable. On the scale used by Fukazawa and Havenith (2009) this corresponds to the transition away from slightly comfortable which corresponds with the findings of this study, with a whole body thermal comfort limit of 0.30. The limitation of their chosen comfort scale was highlighted in Chapter 2 and raised the questions on the difference between comfortable and neutral. The uniform conditions employed in both studies negate the need for a bipolar scale and thus the need for terms extending towards ‘very comfortable’. The differences in the comfort limits highlighted here justify why it is important that subjective responses use clear and logical terms and why cross literature comparisons are not always possible when different scales are used.

Multiple regression analysis was used to determine which individual sites could be used to predict whole body thermal comfort. The relative influence of each location on whole body thermal comfort was identified using the standardised regression coefficients (Havenith & Middendorp, 1990). The findings releaved the following locations in order of importance; lower back, upper back, lower arm, abdomen and chest. Stepwise multiple regression found these areas to best predict thermal comfort, but this does not necessarily imply that the remaining locations are not important. In Table 5.7 the whole body comfort limits of each location suggests that the upper and lower legs are sensitive areas whilst areas of the torso and the lower arms are the least sensitive. This raises the question as to why the latter are included in the equation. It may be related to the fact that the comfort limits only infer which areas are likely to be felt uncomfortable first whereas the degree of discomfort experienced can be predicted by the regression equations. With this in mind it is unsurprising to find all locations of the torso included in the equation due to the amount of sweat produced from these areas which is confirmed by the higher w_{local} values. This suggests that the amount of sweat may be an influential factor on the degree of whole body thermal comfort. As thermal comfort did not reach extreme levels of discomfort further testing is required to check this hypothesis by increasing w_{local} and the thermal discomfort experienced.

5.4.4.2 Local thermal comfort and w_{local}

Local thermal comfort can be predicted using the regression equations in Table 5.5 and the strong significant correlation coefficients ($r^2>0.88$, $p<0.05$) support the reliability of these predictions. As w_{local} increased, local and whole body thermal comfort decreased but the point at which each location becomes no longer comfortable (-1 category vote) occurred differently for each location (see Figure 5.9). Lower comfort limit indicates a highly sensitive area as it only requires a low w_{local} to cause some degree of discomfort. Table 5.8 compares the comfort limits from this study to Fukazawa and Havenith (2009) and Umbach (1982) and discrepancies exist. The results suggest that the lower back, upper legs and lower legs are the most sensitive zone, followed by the abdomen. The lower arm followed by the upper back and chest are the least sensitive areas. Local comfort limits between the upper and lower legs were similar, yet there appears to be a large difference between the upper and lower arms. Both Fukazawa and Havenith (2009) and Umbach (1982) found the limbs to be the most sensitive regions whilst the torso was the least sensitive, particularly the back. However, during their experiment they did not always succeed in creating a clear contrast between target and non target zones, especially for the arms. w_{local} of the torso were relatively high in their tests during the arm and leg condition. This is likely a result of the higher sweat rates found at the torso and lower sweat rates at the limbs (Smith and Havenith, 2011). As stated earlier the present experiment was able to make clear contrast in w_{local} of the target and non-target areas except in the leg condition. As the thermal comfort of the target location was significantly higher than other non-target locations during the leg condition, the data can be used to define the comfort limits of the legs, but its effect on whole body thermal comfort should be used with caution. Upper back w was also slightly above its comfort limit (0.56) (as defined by this experiment) during the leg condition but was significantly lower than the legs. Interestingly the arms were deemed as highly sensitive areas by both Fukazawa and Havenith (2009) and Umbach (1982), yet in this experiment, the upper and lower arms are areas of low sensitivity both locally and the whole body. During the arm condition, all w_{local} of the non target areas were very low and below their comfort limits (as defined by this study). These findings, along with the strength of the correlation coefficient confirm the reliability of these results and oppose claims made by Fukazawa and Havenith (2009) regarding the arms being highly sensitive.

As w_{local} was increased at the target location beyond what may actually occur in uniform clothing, the sensitive areas defined here, such as the extremities, may not be the cause of discomfort in natural conditions as it depends on local moisture production. This is particularly true for the extremities as sweat production is substantially lower than the torso (Smith and Havenith, 2011). Future studies should investigate the influence of w_{local} on thermal comfort in uniform clothing where by w_{local} increases at a natural rate.

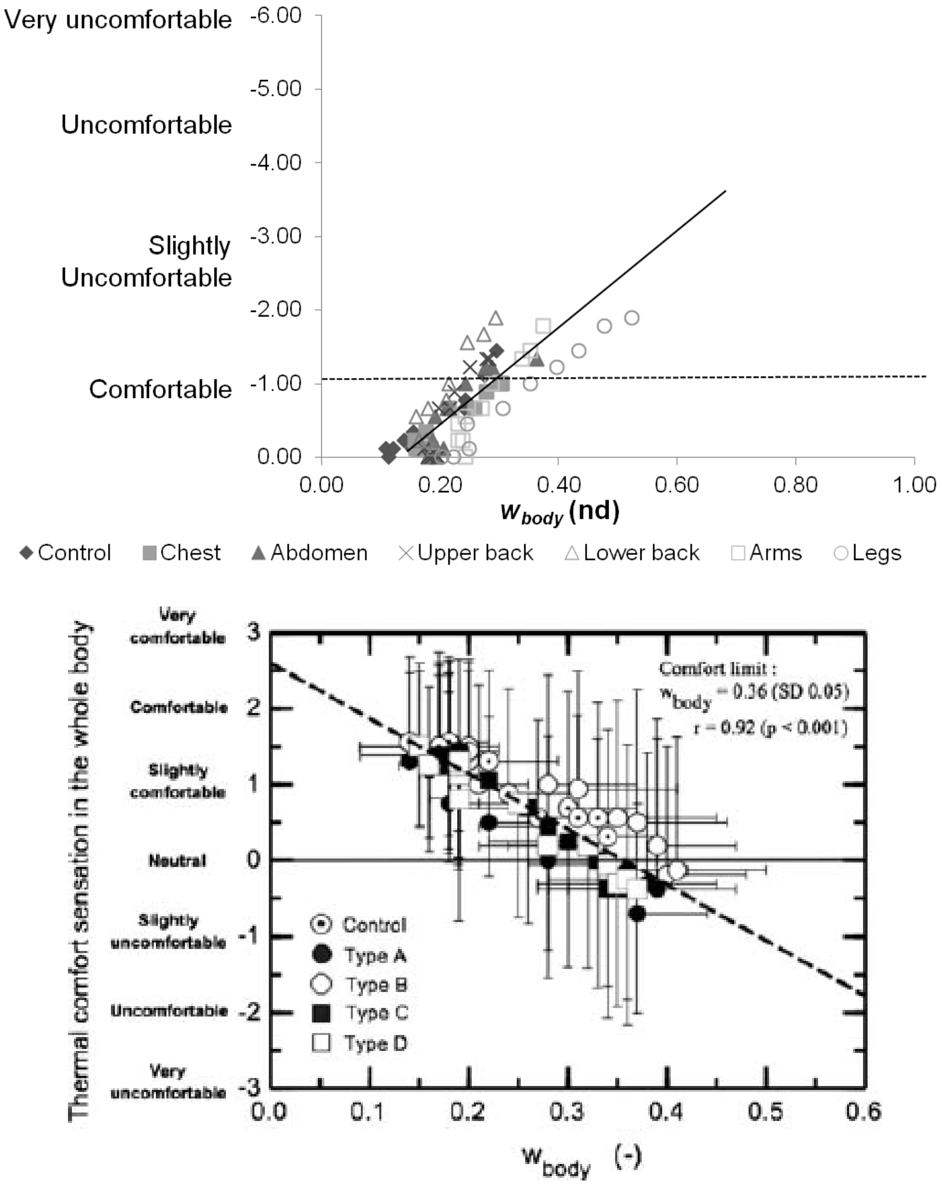


Figure 5.14: A comparison of the whole body thermal comfort limits according to w_{body} used in a) the present study (n=11) and b) Fukazawa and Havenith (2009) (n=8).

5.4.4.3 Whole body and local thermal comfort

Figure 5.12 illustrates the relationship between whole body and local thermal comfort. This indicates that each area, when manipulated, had a similar influence on whole body thermal comfort. There are some differences between zones and how much they influence whole body thermal comfort, but the difference in the most extreme case is half a comfort score (between arms and legs). Generally the slope of the line shifts to the right, indicating that local thermal comfort increases first followed, in a similar manner, by the whole body. Regardless of this difference, when any area of the body becomes uncomfortable (and all other areas remain comfortable) this one zone will gradually influence the whole body comfort in a similar manner. Arens et al. (2005) investigated thermal comfort in uniform environments and this supports their findings that thermal comfort usually followed the most uncomfortable zone. They did find the areas most likely to influence whole body thermal comfort in warm conditions were the hands and face; areas which were not tested in this experiment. However, the concept that an uncomfortable zone will have a similar effect on the whole body was found. From a different perceptive, Pellerin and Candas (2005) found that the number of body parts felt 'thermally unpleasant' was positively correlated with whole body thermal comfort. The findings of the present study do not necessarily dispute their conclusion as the thermal comfort perceived locally and across the whole body only reached 'slightly uncomfortable' scores. Whether the influence of local thermal comfort in more severe cases will have the same effect on the whole body can only be assumed from extrapolating the regression lines, which would suggest no regional differences. This is a concept that would require further investigation.

5.4.4.4 Wetness sensation and skin wettedness

The present study supports previous research regarding the role of w_{local} and w_{body} as a driver of thermal discomfort (Winslow et al. 1939; Gagge, et al. 1969a; Fukazawa and Havenith 2009). Surprisingly however, to the authors' knowledge, the perception of wet skin and its link with w and thermal comfort have never been explored. Many researchers have attempted to understand how humans' sense wet skin (Plante et al. 1995; Li et al. 1995; Bentley, 1990; Hollies et al. 1979) and due to the absence of wet receptors the results have been varied. The change of T_{sk} that is brought about by evaporative cooling has been put forward as a theory of how we sense wetness (Plante et al. 1995; Li et al. 1995; Bentley, 1990; Newton et al., 2007) and the movement of sweat along the surface of the skin stimulates tactile receptors and provides feedback of the presence of sweat. In this experiment, the build up of moisture in the target area was a result of impermeable material over loose fitting clothing. The clothing that was in contact with the skin was uniform across the body regardless of test condition, which aimed to keep the tactile properties similar so not to influence any perceptual responses. Participants could not see any visible sweat, nor were they allowed to touch any areas. The results showed strong correlations between local wetness sensation and w_{local} ($r^2>0.83$, $p<0.05$) and whole body wetness sensation and w_{body} ($r^2=0.88$, $p<0.05$). As w_{local} and w_{body} increased the wetness sensation also increased and as with thermal comfort, the point at which each location feels no longer dry (1 category vote) occurred differently for each location. For the whole body, the wetness limit occurred at 0.30, which corresponds with the comfort limit of the whole body. For local wetness sensations the results indicate that the abdomen, chest, lower back and upper legs are the most sensitive zones as a lower w_{local} is required in order to detect moisture. The upper and lower arms are the least sensitive areas, followed by the upper back. Slight differences are observed between upper and lower legs, yet there appears to be a larger difference between the upper and lower arms.

Higher local wetness limits are observed for the whole body sensation in comparison to local sensation which is tenable as it requires more sweat on one local site before it will influence the whole body. Although the pattern for areas of sensitivity is similar to comfort limits, the thresholds for wetness sensation occur at lower w_{local} than they do for thermal comfort. Table 5.7 displays the local and whole body wetness and comfort limits and it is clear that humans recognise the presence of moisture on the surface before it is perceived as uncomfortable. This supports Nishi and Gagge's (1977) claim that with increasing metabolic rate humans accept more sweat on the skin as it is a natural bodily function that helps cool the skin. The results suggest that there is a point at which w_{local} builds up and starts to feel uncomfortable. The difference between when wetness sensation is perceived and when comfort no longer occurs is greatest at the chest (-0.15), followed by the upper back (-0.09) and upper legs, whereas the lower legs feel wet and uncomfortable at the same time. The moderate correlation coefficient between wetness sensation and thermal comfort supports the link between the two variables. However, as wetness sensation and thermal comfort did not reach high values this statement needs to be checked when participants reach sensations of 'wet' and 'uncomfortable' scores.

After the trial when the clothing was removed, many participants reported that there seemed to be a lot more sweat than they perceived during the experiment. This may suggest that w_{local} was higher than measured, but highlights an inability to sense wetness if we cannot see or touch the target areas. Another factor may be associated with the limited air movement within the clothing. The lack of wet sensing receptors requires individuals to perceive wetness through indirect mechanism such as movement of sweat on the skin, or ventilation causing an increase in evaporative cooling and lowering T_{sk} (Plante et al. 1995; Li et al. 1995; Newton et al. 2007; Nielsen and Endrusick, 1990; Gwosdow et al. 1989). The latter is a frequently reported hypothesis in the literature and may explain why participants in the present study did not experience higher wetness sensations. As the target areas were 'sectioned off' it will have prevented evaporative cooling and thus prevented a drop in T_{sk} which would have reduced the ability to sense wetness. Sweat moving across the skin may have occurred and thus allowed some indication of wetness, although no participant scored a ‘dripping wet’ sensation (category vote of 6). The legs scored the highest wetness sensation, despite the upper legs having one of the lowest w_{local} values at the end of the experiment. The likely cause may be a result of the continual movement of the legs during walking and therefore pumping more air within the microclimate and more frequent contact between the skin and clothing.

5.5 Conclusions

This study aimed to determine the influence of local skin wettedness (w_{local}) on local and whole body thermal comfort and wetness sensation.. The following conclusions were drawn.

- The experimental design successfully created clear contrasts between target and non target locations, confirmed by the differences in both the physiological and perceptual responses.
- Local T_{sk}, $\bar{T}_{sk}$ and T_c remained stable during each condition and were not significantly different between conditions; this confirmed that any changes in perceptual responses were attributed to changes in w_{local}.
- The results showed strong correlations between local and whole body thermal comfort and w_{local} and w_{body} ($r^2>0.88$, $p<0.05$)
- The comfort limit of the whole body, which was defined as w that corresponded with the point at which the individual (or location) becomes no longer comfortable (-1 category vote) occurred at 0.30.
- Differences existed between the present study and that of Fukazawa and Havenith (2009) and Umbach (1972), who found the arms and legs to be the most sensitive areas.
- The thermal comfort limits of each location were identified (in order of high-low sensitivity); lower back (0.40), upper legs (0.44), lower legs (0.45), abdomen (0.45), chest (0.55), upper back (0.56), upper arms (0.57) and lower arms (0.65).
- The results showed strong correlations between w_{local} and local wetness sensation ($r^2>0.83$, $p<0.05$) and w_{body} and whole body wetness sensation ($r^2=0.88$, $p<0.05$). The wetness limit for the w_{body} occurs at 0.30, same as the comfort limit.
- The wetness limit for each location followed a similar pattern to thermal comfort limits however, the thresholds for wetness a sensation occurs at lower w_{local} than for thermal comfort.

- A moderate-strong correlation coefficient between thermal comfort and wetness sensation indicates a strong link between the two variables.

Chapter six – Laboratory study 3

The reliability, reproducibility and validity of galvanic skin conductance and how it should be standardised.

6 Chapter Summary

From the previous chapter and from subsequent pilot tests it was established that an additional predictor of thermal comfort is required when sweat production is high. This was a result of an increasing discomfort score with increasing sweating but a plateau in w_{local} and w_{body}. Therefore an additional predictor required investigation in an attempt to better understand the driving force for discomfort in such conditions. The chosen predictor is galvanic skin conductance (GSC) because of its ability to measure sweat within the skin and on the surface. However, GSC is seldom used in thermophysiological research and there are problems concerning how to standardised this arbitrary measurement. Therefore, this chapter is aimed at assessing the reliability, repeatability and validity of GSC and explore the best methods to standardise the value in two separate experiments.

In the first experiment, GSC is measured during two identical tests on two participants during rest and exercise in a warm room (25.1 ± 1.1°C, 35 ± 4.4%RH). The validity of GSC is assessed by correlating the values against regional sweat rate (RSR), local skin wettedness (w_{local}) and other thermophysiological responses (core temperature (T_c), body temperature (T_b) and skin temperature (T_{sk})). Overall, GSC had a moderate-strong relationship with RSR ($r^2 > 0.60$, $p < 0.05$) and w_{local} ($r^2 > 0.55$, $p < 0.05$). Some significant differences in GSC were observed between the two test conditions, which is likely due to individual variation in sweat gland output. Overall, the findings indicate that GSC is reliable, reproducible and a valid measure of sweat production, although further testing is required to fully understand the measurement.

In a second test, the method of standardisation is explored by attempting to achieve minimum and maximum sweat gland activity in eight participants. Participants sat in a cold room in order to obtain minimal GSC response. Then a maximum response was achieved by exposure to heat (30°C, 50%RH) during an incremental cycling protocol. After obtaining the measurements, GSC was standardised from a change from baseline (ΔGSC), a percentage of its maximum ($GSC_{\%max}$) and relative to its minimum

and maximum value (GSC_{std}). Standardising the value reduces the errors within and between participants and tests and GSC_{std} displayed the smallest standard deviations. This standardisation is relative to a minimum and maximum GSC. However, uncertainties arise when attempting to achieve maximum GSC. Therefore ∆GSC is proposed as the method of standardisation for future research using GSC.

6.1 Introduction

Skin wettedness (*w*) provides information as to how much sweat is present on the skin surface. Once sweat begins to drip off the skin, the efficiency of evaporative cooling diminishes and *w* will be at its maximum (1.0). However, sweat will continually be produced until hidromeiosis occurs or the heat strain lessens. In the previous chapter, *w* was relatively low as was the thermal discomfort experienced, due to the aim of the experiment focusing upon the thresholds for discomfort. In conditions where sweat production is high and discomfort worsened *w* will have a ceiling effect and thermal discomfort is likely to increase. This occurred in subsequent pilot tests and raised the question as to what else is driving discomfort. Research has suggested that the swelling of the epidermis due to the presence of sweat, increases the sensitivity of receptors located within the skin (Berglund and Cunningham, 1986; Berglund, 1995, cited in Arens and Zhang, 2006, p.595). Therefore, it may be that not only will the presence of sweat on the skin, as measured by *w* but also the presence of sweat within the skin affect thermal comfort. Henceforth, an alternative measure of sweat gland activity and information regarding the hydration of the skin may be required to supplement the measurement of *w* when investigating thermal comfort. This chapter will introduce GSC and investigate whether it can be used as a measure of sweat gland activity for thermophysiological research. The reliability and reproducibility of GSC will also be investigated by comparison to regional sweat rate (RSR) and *w*.

6.1.1 Background information

GSC is a measure of the skin's ability to transmit an electrical current, which is enhanced by the presence of the weak electrolyte solution of sweat. As the ducts fill with sweat, GSC increases and as sweat travels towards the surface of the skin, the hydration within the corneum increases. According to Kligman (1964) the corneum is very hygroscopic and can hold up to 70% of its own weight in water. The increase of water within the corneum will increase the conductivity of the skin. The amplitude of the change in conductance depends on the amount of sweat delivered to the duct and on the number of sweat glands activated (Fowles, 1986; Thomas and Korr, 1957;

Edelberg, 1972). Edelberg (1972) provides an in-depth description of the relationship between physiological changes and electrodermal activity, which were discussed in Chapter 2. In summary, GSC will increase when sudomotor activity begins and as sweat rises up the coiled portion of the duct and moves into a relatively dry corneum. As secretion stops sweat will remain in the duct and GSC stabilises. Sweat will either slowly diffuse into the corneum, evaporate, or be reabsorbed into the sweat gland, causing a reduction in GSC. Changes in GSC have been shown to occur even before sweat is observed on the skin surface (Darrow, 1964). As a result, the measured changes in GSC have been associated with the pre-secretory activity of the sweat glands, the filling of the sweat ducts and the hydration status of the corneum. However, whether the amount of sweat present on the skin surface influences GSC remains unknown.

The electrical properties of the skin can be measured via an exosomatic technique, which involves placing two electrodes on the skin and putting a small fixed voltage on them and allowing the current to flow. The skin behaves as a resistor which can be measured using Ohms Law:

$$R = \frac{V}{I}$$

Where;

R resistance

V voltage

I current

From this, two related measurement variables can be obtained; resistance, measured in ohms (Ω) and conductance, which is the reciprocal of resistance and is measured in microsiemens (µS). As GSC is dependent on a number of parameters (e.g. dry skin conductance, distance of electrodes, electrode-skin contact), the actual value is an arbitrary unit and it cannot necessarily be compared between individuals or locations in its base form. This will now be discussed in more detail. The electrical properties of the skin vary for a given individual due to psychological, structural and/or physiological factors. For psychological research, changes in autonomic sympathetic arousal associated with anxiety and emotions have been measured using GSC. However, the baseline GSC may vary depending on an individual's current psychological state or in anticipation of the subsequent test protocol. In such studies, GSC is usually measured at the hand (Machado-Moreira et al. 2009; Armel and Ramachandrun, 2003; Edelberg, 1967); a glaborous area associated with psychological sweating (Iwase et al. 1997). To counteract this issue, many researchers will collect baseline values during complete relaxation, or even sleep (Edelberg, 1972). However, ensuring complete relaxation is not always plausible, therefore a familiarisation session may be required in order to ensure participants are aware and at ease with the test protocol.

Measurement errors due to the placement of electrodes onto the skin are highly probable due to the difficultly in measuring the same locations in successive tests. The measurement area should be standardised for each participant as the stratum corneum thickness varies across the body and between genders (Sandby-Møller et al. 2003; Tortora and Derrickson 2006). The thickness of the skin may too have an influence on GSC, but the exact measurement depth of many GSC devices is unknown. For psychophysiological studies, the measurement area is typically standardised at the dorsal surface of a distal phalange (Edelberg, 1972). However, to measure GSC across the body, standardising the measurement area is important, particularly as body morphology varies between participants. As GSC is itself influenced by the presence of sweat, the density and distribution of sweat glands within a given measurement site will also influence the value (Thomas and Korr, 1957; Edelberg, 1972). Research has demonstrated individual differences in RSR and sweat composition within and between participants (Havenith et al. 2008; Patterson et al. 2001; Smith and Havenith, 2011). Alongside this, GSC is influenced by keratin, which is located in the most superficial layer of the skin; the epidermis (Edelberg, 1972). When applying electrodes to the skin, it is important to reduce any noise in the data that could result from skin surface interference. With electromyography (EMG) measurements, the skin is abraded and wiped with alcohol, however this is not recommended for GSC as abrading the skin will remove the keratin from the epidermis which contributes to the skins conductance (Edelberg, 1972). It is important to cleanse the skin with deionised water to remove any chemical agents or electrolytes on the skin surface.

As GSC is an arbitrary unit and due to the number of potential measurement errors, both systematic and unsystematic, it is important that GSC is standardised. In the literature GSC is often expressed in terms of absolute values and some researchers have attempted to standardise the measurement (Lykken et al. 1966; Lykken and Venables, 1971; Rose, 1964). Rose (1964, cited in Lykken et al. 1966, p.482) first described an index which represented an individual's skin potential relative to the participants own estimated limits of variation. This was later amended to account for GSC by Lykken et al. (1966) using the following equation:

$$GSC_{std} = \frac{(GSC_{ix} - GSC_{min})}{(GSC_{max} - GSC_{min})}$$

Where,

GSC_{std}	standardised skin conductance (µS)
GSC_{ix}	raw value of obtained from the subject (i) in a given situation (x)
GSC_{min}	minimum value obtained (µS)
GSC_{max}	maximum value obtained (µS)

The equation requires estimating a minimum and maximum value to reduce variations and allowing the value to be proportional to the individual being tested. Lykken and Venables (1971) claimed that this would allow them to focus primarily on data that is associated with psychological factors; however whether this will apply for thermoregulatory research is uncertain due to difficulties obtaining minimum and maximum values. In psychophysiological research, minimum values have been achieved by monitoring GSC during complete relaxation or sleep. Maximum values have been obtained with participants blowing up a balloon until it burst, which would startle the participant causing a sharp rise in GSC. However for thermal physiological research the range in GSC is likely to substantially exceed those achieved in psychological research and alternative techniques are required to attain the minimum and maximum values for sweat gland activity. For the former, sedentary activity during cold exposure could be employed and the latter through high intensity exercise in hot conditions. Minimal sweat gland activity is easily achieved, yet uncertainties exist over whether maximal sweat production has been reached. The concept is similar to that used when measuring skin blood flow and the minimum and maximum values are attained by blood occlusion and local heating, respectively. To achieve maximum values, possible techniques for GSC could be through stimulating the sweat glands with cholinergic agonists (pilocarpine, acetylcholine or methacholine) via intradermal injections or iontophoresis (Vimieiro-Gomes et al. 2005). However, some pilot tests carried out by the author at Kobe University (2011) and iontophoresis resulted in an unresponsive GSC value despite an increase in sweat rate as measured by a ventilated sweat capsule (unpublished data). As GSC may be influenced by sweat present on the skin surface; the maximum value might be enhanced after heavy exercise in the heat by spraying an artificial sweat solution, similar to the composition of sweat onto the skin surface. However, this technique requires further investigation.

Using the equation above, Rose (1964, cited in Lykken et al. 1966, p.482) reduced the error of variance and thus increased the correlation with the psychological stimuli compared to using raw data; alongside this Rose found the power of the significance increased. The data should be used with caution as the values calculated are based on estimations of minimum and maximum values. Alongside this Lykken and Venables (1971) suggest that it is not correct to assume that the mechanisms responsible for changes in GSC are related to the factors which determine baseline values. They state that the minimum GSC will always be zero and therefore GSC_{min} should be disregarded from the equation and the value should be corrected. However, according to Grimnes (1982) the stratum corneum is never truly dry, as water content is in balance with the humidity of the air (at skin temperature). Alongside this, the theory of insensible perspiration suggests there is a constant, if small, transfer of sweat to the environment (Gagge, 1937). It is more likely to have a stable minimum value as opposed to an absolute zero. A more appropriate method is that which is used for the assessment of skin blood flow using Laser Doppler flow technique (Johnson et al. 1984; Bircher et al. 1994; Cracowski et al. 2006). During this test, a maximum value will be achieved and values are then expressed relative to individuals and to local sites. The equation proposed by Lykken and Venables (1971) will be altered slightly to express the value as a percentage:

$$GSC_{\%max} = \frac{(GSC_{ix})}{(GSC_{max})} * 100$$

Where,

$GSC_{\%max}$ A range corrected value of skin conductance (%)

A final method of expressing GSC is Wilder's the so-called 'Law of Initial Values' (Wilder, 1962) According to Wilder (1962), the size of a response to an experiment is related to the prestimulus level of the variable under observation. This assumes that the response is a function of the stimulus itself, but also the state of the organism at the time (Lykken and Venables, 1971). It is feasible to determine the response of an individual to a stimulus (whether psychological or thermally induced) in relation to their baseline values, which has been previously done in a combined thermoregulatory and psychological study of sweat gland response (Machado-Moreira et al. 2009). The magnitude of change would be much greater in thermoregulatory research than psychological research, but the principle remains the same.

6.1.2 Aims

The general aim of this chapter is to explore the measurement of GSC and understand the basic principle of the measurement by carrying out several tests. The first aim will be to assess the reliability and reproducibility of GSC to determine whether it can be used as a measure of sudomotor activity. The second aim is to determine the most appropriate method to report GSC for thermoregulatory research.

The first aim (Objective 1) will be achieved by validating GSC against RSR, using the absorbent pad technique (Havenith et al. 2008; Smith & Havenith, 2011) and local skin wettedness (w_{local}), using humidity sensors. Although w_{local} and RSR using the absorbent pad technique are not gold standards for what they measure, they do provide some indication of sweat gland activity. Therefore the data from these techniques will be used to indicate to some extent the validity of GSC as a measure of sweat gland activity. Pearson's correlation coefficient will be used to compare GSC with RSR and w_{local} independently.

The second aim (Objective 2) will be achieved by inducing minimal and maximal GSC via exposure to two different conditions that aim to suppress and augment sweat gland activity. Further to this, application of artificial sweat will be assessed to determine whether this will further increase GSC once sweating is assumed as maximal. GSC will then be standardised according to the suggestions in the literature and the most appropriate method assessed using correlation analysis against other sweat parameters. The nature of this research is exploratory and the technique which is consistently highly correlated with the majority of thermoregulatory responses will be deemed the method for standardisation for this thesis.

6.2 Methods

The tests carried out for this chapter are comprised of two pilot tests. Some of the fundamental test protocols are outlined in Chapter 3, but a summary with specific details for each of the pilot tests will be outlined separately here.

6.2.1 Study 1 – Objective 1

6.2.1.1 Participants

Two males were recruited from the staff and student population at Loughborough University.

6.2.1.2 Experimental Design

The aim of this experiment is to assess the reliability and reproducibility of GSC as a measure of sweat gland activity. A repeated measures design was selected with each participant acting as their own control. Participants were requested to visit the laboratory on two occasions at the same time of day with at least 1 day separating trails. Both visits to the laboratory consisted of the exact same protocol to assess the reproducibility of GSC. During each trial GSC, RSR and w_{local} were measured simultaneously to assess the reliability and to some extent assess the validity of GSC. All experiments were conducted in a temperature controlled room, held at 25 ± 1.1°C, 35 ± 4.4% *RH* in the Environmental Ergonomics Research Centre (EERC), Loughborough University, UK.

6.2.1.3 Clothing

Each participant dressed in the required clothing, which consisted of running shorts plus, a 100% polyester long sleeve top with a high permeability for heat and vapour transfer with total thermal resistance of 0.154 $m^2 \cdot K \cdot W^{-1}$ and total water vapour resistance 35.9 $m^2 \cdot Pa \cdot W^{-1}$ all tested on a thermal manikin (Newton, Measurement Technology Northwest, USA). They also wore their own personal socks and athletic trainers.

6.2.1.4 Methodology

Upon arrival to the laboratory, participants' stature and body mass (pre and post test nude) were recorded during both visits. The back was chosen as the measurement area due to the high RSR reported from this region (Smith and Havenith, 2011) and the ease of access. The area was cleansed with deionised water and dried with sterile towels. Following this, three sets of pre-gelled electrodes were attached for the measurement of GSC using MP35 Biopac System (Goleta, California, USA), with a sample rate of 1 sample$\cdot s^{-1}$. A humidity sensor was placed in between the electrodes to keep them at an equal distance apart (~3.0 cm). The most medial electrode (right) was positioned 3cm from the centre of the spinal column. The most lateral electrode (left) was positioned so that it was adjacent to the right electrode with 0.5cm separating it from the right electrode. Another set of electrodes (beneath) were placed below the left and right electrodes with the lateral electrode positioned beneath the inferior ridge of the scapula. Figure 6.1 illustrates the sensor application to the skin and the corresponding names given for analysis and discussion.

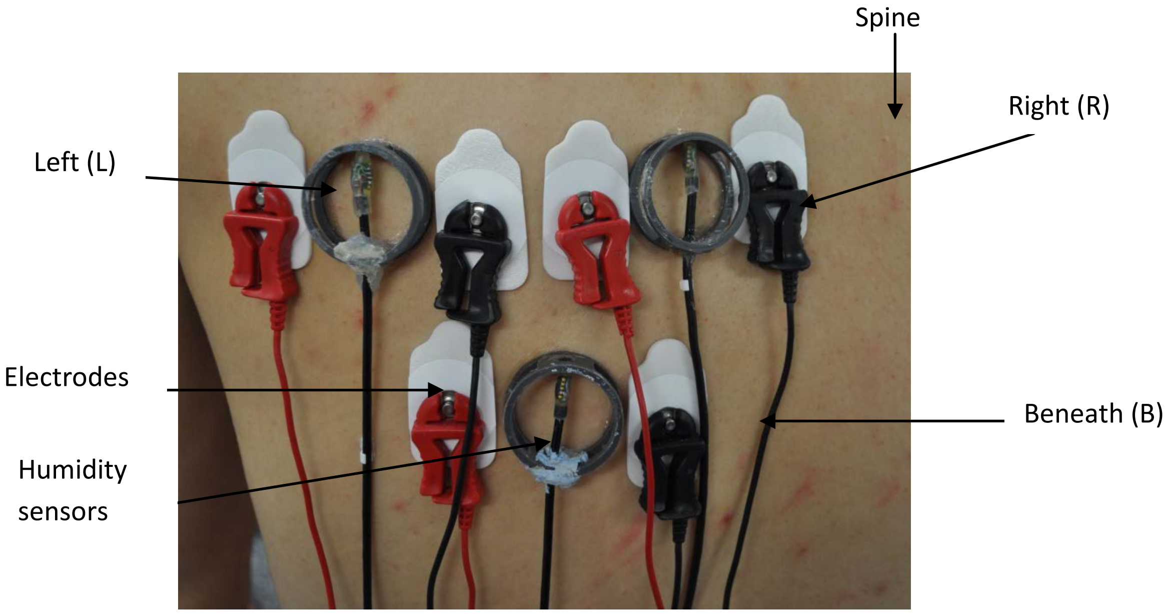


Figure 6.1: The electrode sensors to measure GSC and the humidity sensors to measure skin wettedness at the following locations on the scapula: Right (R), left (L) and beneath (B).

Above this area RSR was also measured using the sweat absorbent pad technique (see Havenith et al. 2008). In brief, this technique measures RSR via placing absorbent pads (Product 2164- Laminated Airlaid, Tech Absorbents, Grimsby, UK) onto the skin, for a set period of time to absorb the sweat produced. Firstly, airtight zip-lock bags are individually labelled for each pad and weighed using electronic scales (Satorius, YACOILA, Satorius AG, Goettingen, Germany, Resolution 0.01g). The corresponding pad was placed inside the bag and the weight recorded. The pad is then applied to the skin for a period of 5 minutes after which it is placed back into the airtight bag and reweighed. RSR was calculated from the weight change of the pad, the surface area and the duration of application. The surface area of each pad was calculated using the following equation:

$$SA = \frac{w_d}{\left[\left(\frac{w_c}{a_c}\right) \cdot 10000\right]}$$

Where;

SA surface area (m^2)

w_d dry weight of material (g)

w_c weight of control material (g)

a_c areas of control material (cm^2)

RSR was calculated using the following equation:

$$SR = \frac{\left[\frac{(w_w - w_d)}{SA}\right]}{t} \cdot 3600$$

Where,

SR Sweat rate ($g \cdot m^{-2} \cdot h^{-1}$)

w_w wet weight of pad (g)

w_d dry weight of pad (m^2)

t time, duration of pad application (s)

Once dressed and fully equipped, participants rested for 15 minutes in a temperature controlled room at 25 ± 1.1°C, 35 ± 4.4% *RH*. During the last 5 minutes of rest an absorbent pad was applied to the upper back, after 5 minutes the pad was removed, placed in an air tight bag and weighed. The participants began cycling at 100W at 60RPM for 15 minutes, which was then increased to 70RPM for 15 minutes, followed by 15 minutes rest to obtain post-exercise values. During the trial, absorbent pads were applied for 5 minute periods and all other physiological data was averaged over 5 minute periods.

6.2.2 Study 2 – Objective 2

6.2.2.1 Experimental Design

The aim of study 2 was to determine the most appropriate method of standardising GSC for thermoregulatory research and assess whether applying artificial sweat onto the skin surface can maximise the GSC value. Participants were required to visit the laboratory on one occasion each.

6.2.2.2 Participants

Eight males were recruited from the staff and student population at Loughborough University.

6.2.2.3 Clothing

Each participant dressed in the required clothing, which consisted of running shorts, plus a sports bra for females and their own personal socks and athletic trainers.

6.2.2.3 Methodology

Pre and post-test nude weight was recorded in kg using electronic balance scales during each visit. Participants self inserted a rectal probe 10 cm beyond the anal sphincter. Each participant wore a Polar heart rate monitor (Polar Electro Oy, Kemple, Finland). Following this, each participant dressed in the required clothing and three skin thermistors and three temperature/humidity sensors were attached to the skin at the following locations; scapula, triceps and quadriceps. Once fully equipped, participants rested for a period of 30 minutes in the experimental room (15°C, 40%) to allow physiological responses to stabilise. During sedentary activity, artificial sweat as proposed by ISO 3160-2 (comprised of 20 g·l NaCl, 17.5 g·l NH4Cl, 5 g·l acetic acid and 15 g·l lactic acid with the pH adjusted to 4.7 by NaOH) was sprayed onto three individual areas (scapula, triceps and quadriceps) for 5 minute periods, after which each area was dried. Following this, participants moved to an environmental chamber (30°C, 50% RH) were they rested for 10 minutes prior to cycling at 105 watts at 60RPM for 10 minutes, followed by 160 watts at 80RPM for 20 minutes. During the last 5 minutes of exercise, artificial sweat was sprayed once again onto the three individual areas. After exercise, participants rested for 5 minutes in the environmental chamber. All physiological and environmental measurements were recorded at 10 second intervals and 5 minute averages were taken for analysis.

6.2.2.3.1 Standardisation of GSC

Four methods of expressing GSC will be investigated. Firstly, absolute values of GSC (μS) will be reported (GSC_{raw}). Secondly a percentage change (%) in GSC based on maximum values will be reported ($GSC_{\%max}$) using the following calculation:

$$GSC_{\%max} = \frac{(GSC_{ix})}{(GSC_{max})} * 100$$

Where,

$(GSC_{\%max})$ A range corrected value of skin conductance (%)

GSC is expressed as a change from baseline values (ΔGSC), as described by the Wilders law of initial values (Wilder, 1962) will be calculated using the following equation:

$$\Delta GSC = GSCix - GSC_0$$

Where,

ΔGSC change of skin conductance from baseline (µS)

GSC_{ix} raw value of obtained from the subject (i) in a given situation (x)

GSC_0 initial value of skin conductance (µS)

Finally, a standardised GSC (GSC_{std}) (µS), calculated using the equation below.

$$GSC_{std} = \frac{(GSC_{ix} - GSC_{min})}{(GSC_{max} - GSC_{min})}$$

Where,

GSC_{std} standardised skin conductance (µS)

GSC_{ix} raw value of obtained from the subject (i) in a given situation (x)

GSC_{min} minimum value obtained (µS)

GSC_{max} maximum value obtained (µS)

GSC_{min} was obtained from the minimum value recorded throughout the duration of the test, this was not necessarily the first value recorded. GSC_{max} was obtained from the maximum value recorded, which was not necessarily the final value recorded.

6.3 Results

6.3.1 Study 1

The aim of study 1 is to assess the reliability and reproducibility of GSC in comparison to RSR and w_{local}. This will help determine whether it can be used as a measure of sudomotor activity. Although the expression of GSC is not the main outcome of study 1, it does provide informative data, which will be discussed prior to the assessment of the reliability and reproducibility of GSC. Initially GSC was graphed for each method of standardisation over time for each test. All graphs were compared to GSC_{raw} to determine any variation between location and condition for each participant (Figure 6.2a-h). GSC_{std} and $GSC_{\%max}$ contain the least amount of variation between locations and test conditions. GSC_{raw} and ΔGSC are low and stable during the first 15 minutes of the test and the variation between sites and test conditions is minimal. Once GSC_{raw} increases the variation increases both between measurement sites and tests. This variation is reduced when the values are standardised.

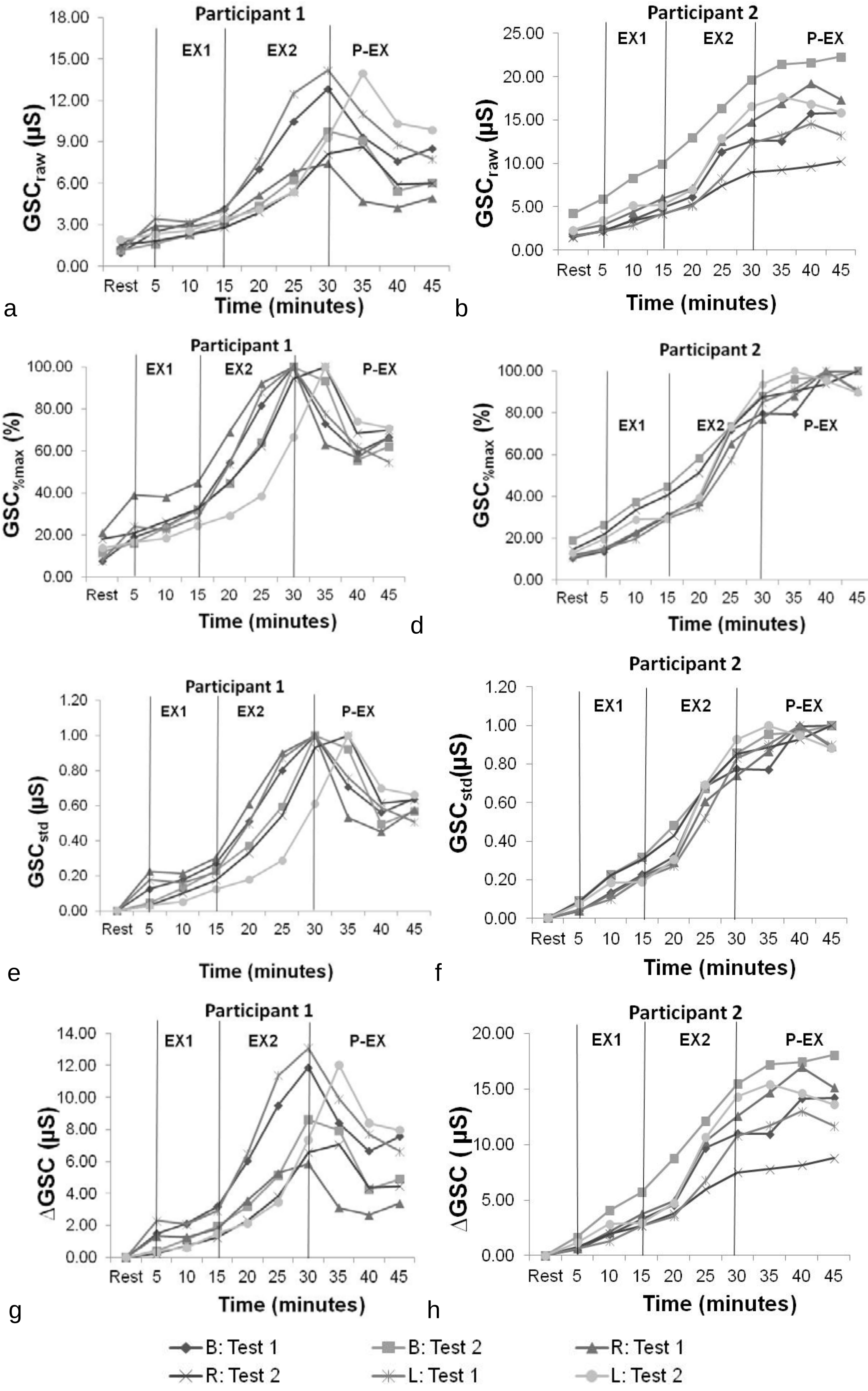


Figure 6.2: Individual GSC values for participant 1 (left) and 2 (right) measured at three locations on the scapula; (R: right, L; left and B; beneath) during test 1 and test 2. Each standardisation is presented (a-b; GSC_{raw}, c-d; $GSC_{\%max}$, e-f; GSC_{std}, g-h; ΔGSC).

Paired sample t-tests were carried out to determine any differences between test 1 and test 2 for each participant and the results are displayed in Table 6.1. Correlation analysis revealed significant high correlations between the measurement sites on test 1 and test 2 for each type of standardisation ($r^2 > 0.72$, $p < 0.05$).

Table 6.1: The significance level between test 1 and test 2 for Participant 1 (*p<0.05) and Participant 2 (#p<0.05) at each location.

	GSC_{raw}	$GSC_{\%max}$	GSC_{std}	ΔGSC
Right	#	*	#	#
Left	#	*	#	#
Beneath	#*	#*		#*

Figure 6.3a-h illustrate the relationship between each form of standardisation of GSC and RSR for participant 1 and 2. The data points inside the circles correspond to the measurements post exercise. Post exercise RSR decreases at a faster rate than GSC. Pearson's correlation coefficient was calculated with and without post exercise data. The results revealed a high significant correlation between GSC and RSR with post exercise but much higher without post exercise data ($r^2 > 0.60$, and $r^2 > 0.75$, $p < 0.05$, respectively). The only exception to this rule is participant 2 during test 1 where the relationship was weak and non-significant with post exercise data ($r^2 < 0.200$, $p > 0.05$). The strength of the relationship for participant 2 test 1 improved when post exercise data was removed from the analysis ($r^2 > 0.75$, $p < 0.05$). Figure 6.4a-h illustrates the relationship of each standardised GSC with w_{local} and the data points inside the circles correspond to the measurements post exercise. w_{local} does not decrease as quickly as RSR and Pearsons correlation coefficient revealed a moderate-high significant correlation with and without post exercise data ($r^2 > 0.55$ and $r^2 > 0.60$ $p < 0.05$).

Main findings:

- Strong significant correlations existed between GSC measured at each location on the scapula ($r^2 > 0.72$, $p < 0.05$);
- Strong significant correlations existed between GSC and RSR ($r^2 > 0.75$, $p < 0.05$) and w_{local} ($r^2 > 0.60$, $p < 0.05$);
- RSR declined at a faster rate than GSC and w_{local} post exercise.

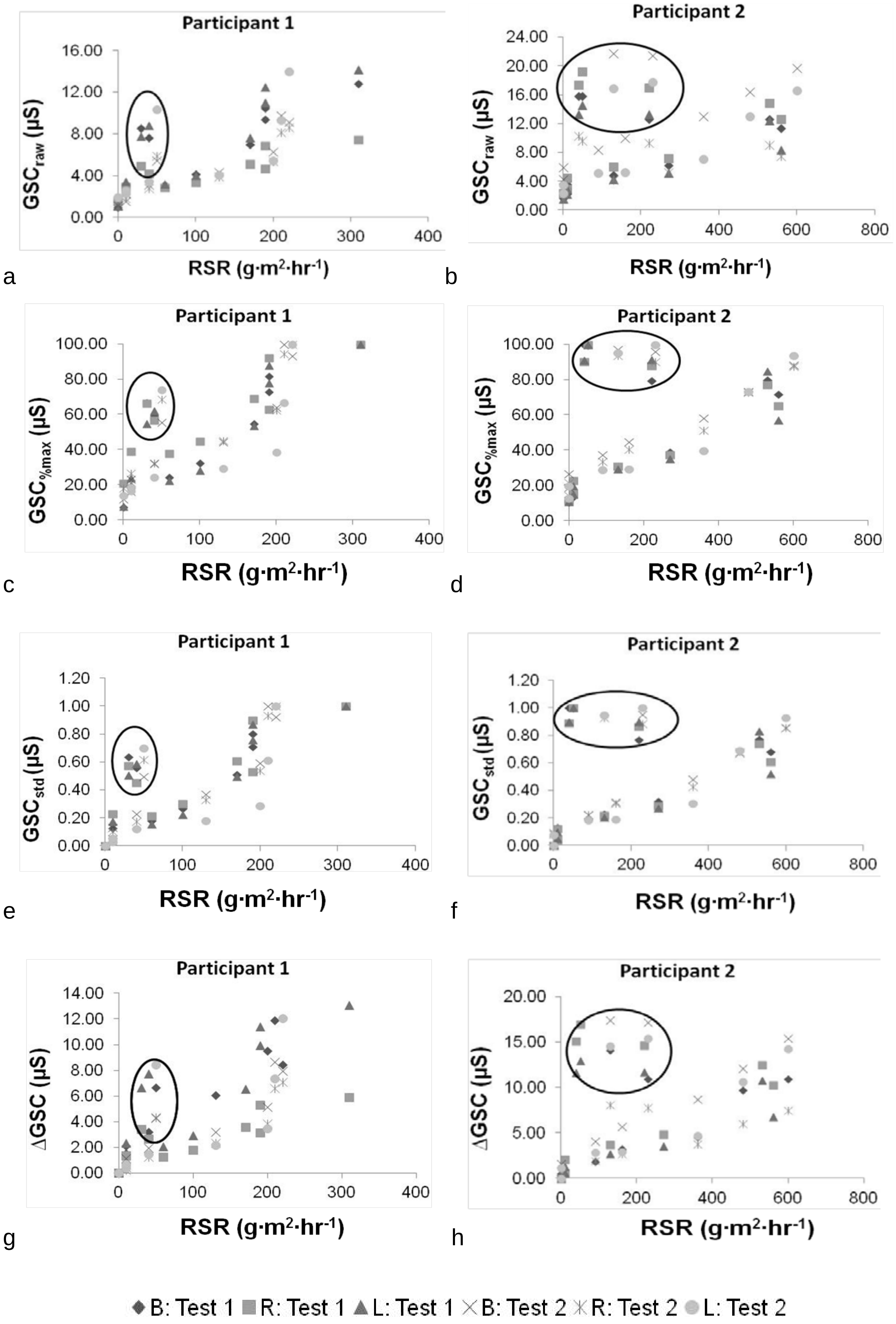


Figure 6.3: The relationship between GSC and RSR for participant 1 and 2 during both test 1 and 2 measured at three locations on the scapula; (R: right, L; left and B; beneath) during test 1 and test 2. Data points inside the black circles indicate post exercise. Each standardisation is presented (a-b; GSC$_{raw}$, c-d; GSC$_{\%max}$, e-f; GSC$_{std}$, g-h; ΔGSC).

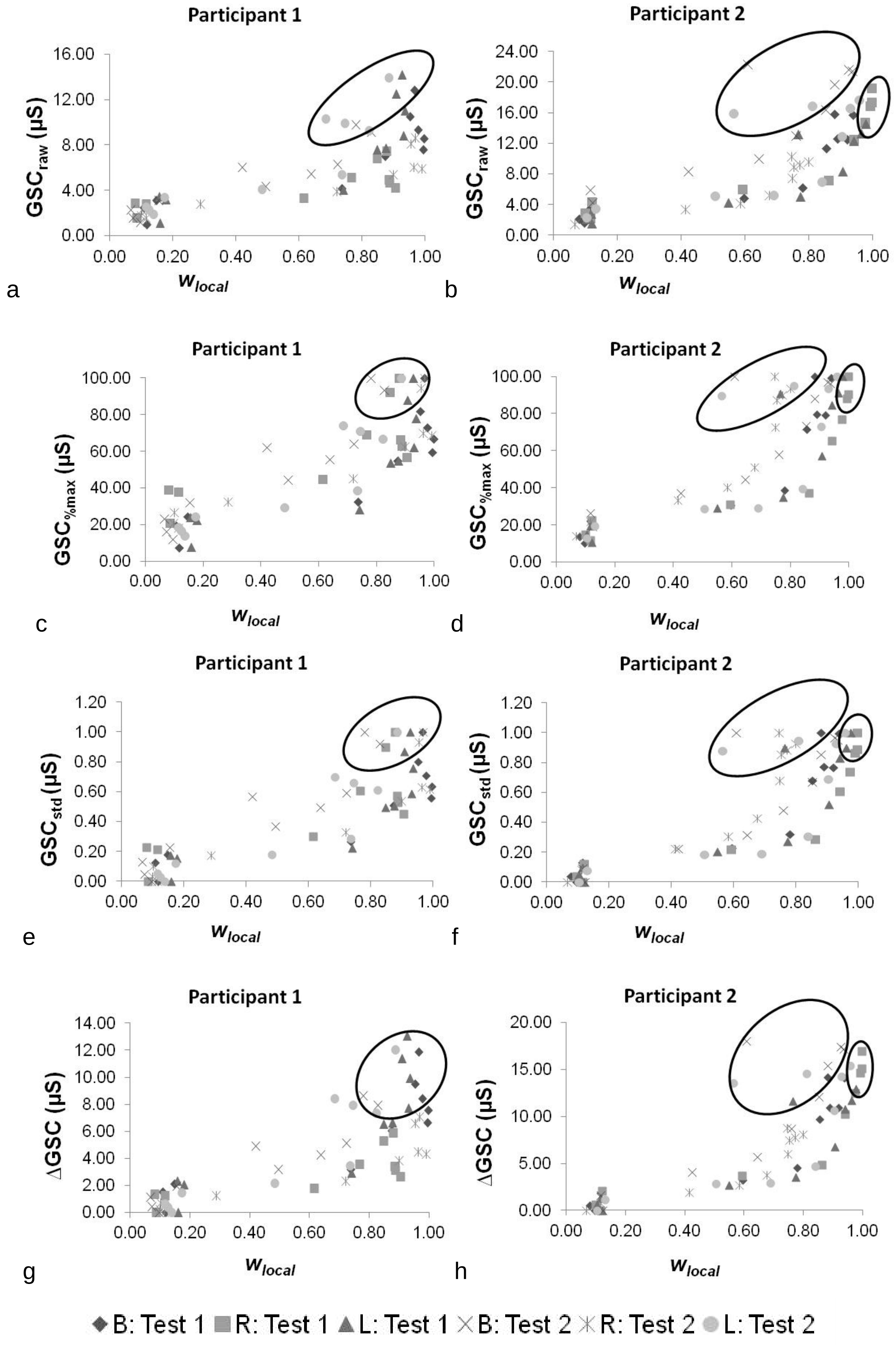


Figure 6.4: The relationship between GSC and wlocal for participant 1 and 2 during both test 1 and 2 measured at three locations on the scapula; (R: right, L; left and B; beneath. Data points inside the black circles indicate post exercise data. Each standardisation is presented (a-b; GSC$_{raw}$, c-d; GSC$_{\%max}$, e-f; GSC$_{std}$, g-h; ΔGSC).

6.3.2 Study 2 – Objective 2

The aim of study 2 was to determine the most appropriate method of standardising GSC for thermoregulatory research and assess whether applying artificial sweat onto the skin surface can maximise the GSC value. Figure 6.5 illustrates GSC during the trial for the four methods of expression; GSC_{raw}, $GSC_{\%max}$, ΔGSC and GSC_{std}. GSC follows a similar pattern throughout the trial for each type of standardisation. The standard deviation (SD) is largest for GSC_{raw}, followed by $GSC_{\%max}$, then ΔGSC, whilst GSC_{std} displayed very small SD.

As an indication of the thermoregulatory response, correlation analysis was carried out on each GSC standardisation with the following physiological responses; mean T_c ($\bar{T}_c$), T_b ($\bar{T}_b$) and $\bar{T}_{sk}$. Data points obtained when sprayed with sweat were removed before analysis. This was deemed appropriate as spraying artificial sweat onto the skin surface is an unnatural mechanism and likely to reduce the relationship between the physiological responses. Table 6.2 displays the results from the correlation analysis. Each method of standardisation was highly correlated with T_c, T_b and $\bar{T}_{sk}$ but ΔGSC was the strongest on two occasions (with T_b and $\bar{T}_{sk}$). When exposed to the cold, participants were inactive, resulting in low and stable responses for T_c, T_b and T_{sk}. During this time GSC was also stable, but as participants moved into the warmth GSC began to increase. This was mirrored by $\bar{T}_{sk}$.

Table 6.2: The relationship (r^2) between each form of standardised GSC with T_c, T_b and $\bar{T}_{sk}$. * denotes value of significance ($p<0.001$).

	GSC_{raw} (µS)	$GSC_{\%\,max}$ (%)	ΔGSC (µS)	GSC_{std} (µS)
T_c	$r^2=0.72$*	$r^2=0.75$*	$r^2=0.73$*	$r^2=0.70$*
T_b	$r^2=0.81$*	$r^2=0.82$*	$r^2=0.83$*	$r^2=0.72$*
$\bar{T}_{sk}$	$r^2=0.75$*	$r^2=0.74$*	$r^2=0.79$*	$r^2=0.61$*

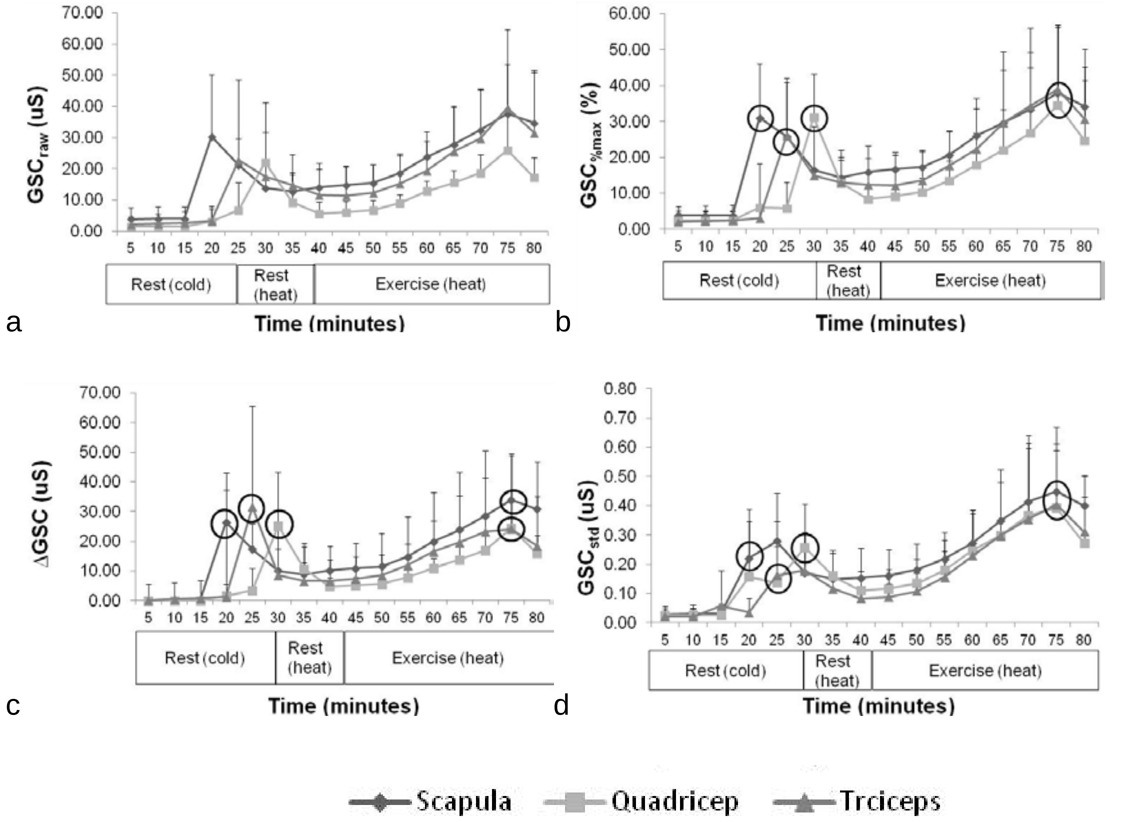


Figure 6.5: Mean (±SD) GSC measured during the trial, expressed in a) *GSC$_{raw}$* b) GSC$_{\%max}$, c) ΔGSC, d) GSC$_{std}$. Values inside the circle indicate when sweat was sprayed onto the respective test area.

Spraying artificial sweat onto each of the measurement sites caused a sudden spike during the rest period, as indicated by the data points in the circles in Figure 6.5. Only a slight increase in GSC was observed at the end of the exercise period, but this did correspond with the highest values scored for each location.

Main findings:

- Strong correlations existed between GSC (all forms of standardisation) and T_c , T_b and mean T_{sk} (r^2>0.70);
- Small standard deviations were observed for GSC_{std} and ΔGSC in comparison to GSC_{raw} and $GSC_{\%max}$;
- Spraying artificial sweat caused a substantial increase in GSC during rest but it had less influence during exercise.

6.4 Discussion

The aim of this chapter is to explore GSC as an indicator of sudomotor activity and assess its reliability, reproducibility, validity and how it should be standardised in a series of pilot tests. The main findings were:

- The response of GSC will be consistent between tests but the actual values collected will be different, regardless of how it is standardised.
- GSC has a strong relationship with RSR, w_{local} and other thermophysiological measures (T_c, T_b and T_{sk}).
- GSC declines at a faster rate than indicated by RSR and w_{local}.
- GSC can be standardised in many ways and they all are highly correlated with physiological responses (T_c, T_b and $\overline{T}_{sk}$).
- The result showed that GSC_{raw} had the largest standard deviations (SD), whilst GSC_{std} displayed the smallest throughout the trial and at each location.

6.4.1 The reliability, validity and reproducibility of GSC

Study 1 aimed to investigate the reliability and reproducibility of GSC as a measure of sweat gland activity. This was tested by two means, firstly Pearson’s correlation between GSC (in all standardised forms) from the two identical test conditions. Figure 6.3 illustrates these relationships and the variation between locations and tests are small for $GSC_{\%max}$ and GSC_{std} whilst they appear much larger for GSC_{raw} and ΔGSC. Although exact values differ between tests, the response of GSC is similar suggesting to some extent that it can be reproduced. In a second method to assess GSC’s reliability and reproducibility using the same data, a paired sample t-test between test 1 and test 2 for each individual participant was carried out. The results suggest significant differences between tests for nearly all standardised forms of GSC for each participant. Surprisingly, this was not limited to the raw data but also to each form of standardisation. It is well established that sweat responses to exact protocols will not always produce similar responses and individual day-to-day variation exists (Kuno, 1956; Szabo, 1962; Randall, 1947). The significant differences found between tests are likely to be a result of this variation. The two methods to assess its reliability and reproducibility suggest that the response of *GSC* to the exact protocol will be consistent but the actual values collected will be different. Unfortunately this is a common issue with GSC which is augmented by the large variations in sweat gland response.

The results indicated a strong, significant relationship between GSC and w_{local} and RSR, which supports the findings from Thomas and Korr (1957). Skin wettedness has a tendency to reach high values very quickly, followed by a plateau close to 1.0. GSC on the other hand, demonstrates a gradual increase towards a peak, without displaying any signs of a plateau (see Figure 6.4). This may explain why the correlation between GSC and w_{local} was not as high as expected and why Figure 6.4a-h have a cluster of data points near 0.20 and >0.8 with large gap in between. According to Thomas and Korr (1957), GSC will increase depending on how much sweat is delivered to the duct and on the number of sweat glands activated. Therefore GSC may reflect the process of sweat production more closely than w_{local} and is unlikely to have a ceiling effect. The relationship between GSC and RSR was high, particularly when post exercise data is removed. Although the technique used to measure RSR is not gold standard measurements, the relationship between GSC, RSR and w_{local} suggests that GSC has potential use as an additional measure of sweat production. Ventilated capsule methods may be a useful tool to measure alongside GSC as a time response could be investigated. This could confirm the findings of GSC indicating pre-secretory sweat gland activity as claimed by Darrow (1964). Additionally, this investigation was employed on two participants; therefore the confirmation of validity may be flawed. Investigations with larger sample sizes and alternative means of measuring RSR could provide more conclusive answers to any issue of validity. The results from study 2 also indicate a strong relationship between GSC and other thermophysiological responses. GSC increased when exposed to warm conditions and further increased during exercise reflecting an increase in sudomotor activity. Results showed a strong relationship of each form of standardisation of GSC with other physiological responses associated with thermoregulation (see Table 6.2). Machado-Moreira et al. (2009) also investigated GSC during thermal and psychological stress tests. They found an increase in ∆GSC (0.50 ± 0.1 to 7.06 ± 1.0 µS) from exposure to heat alongside changes in T_c (36. ± 0.1 to 36.7 ± 0.1°C), $\bar{T}_b$ (35.8 ± 0.1 to 36.4 ± 0.1°C) and sweat rate (0.21 ± 0.02 to 0.66 ± 0.1 $mg{\cdot}cm^{-2}{\cdot}min^{-1}$). These changes were larger in the thermal stress than those experienced during their psychological stress test. The strong relationship between GSC, RSR, w_{local}, $\bar{T}_c, \bar{T}_b$ and $\bar{T}_{sk}$ confirms the usability of GSC as a monitoring device for sudomotor activity and thermoregulation.

The relationship between GSC and RSR is much stronger when post exercise data is removed. This is due to the quick decline in sweat production, but a slower response in GSC post exercise. The slower response in GSC may be due to a high amount of sweat still contained within the sweat glands during post exercise that is no longer released to the sweat ducts on the skin surface. An additional reason as to why GSC did not decline as quickly as RSR is due to the electrodes on the skin surface. When sweat is produced it is released onto the skin surface and either evaporates, is absorbed by the pads (for RSR) or contained within the contact point on the electrode. The absorbent pads are replaced and thus sweat removed, whilst the sweat contained within the contact point of the electrode, is unable to evaporate. This would result in an elevated GSC above that measured at rest even if sweat production had ceased and the epidermis completely dry.

Study 2 aimed to monitor GSC during sedentary activity in the cold when sudomotor activity is assumed to be minimal. The investigation also aimed to monitor the same response during exercise in hot conditions when sudomotor activity is close to maximum. The influence of sweat (artificially sprayed) on the skin surface when sudomotor activity was low, was also investigated. The reason for spraying artificial sweat onto the skin surface was to determine how much sweat on the surface influenced GSC when sweat gland activity is assumed to be minimal. The results clearly indicate low and stable response during sedentary activity when exposed to cold temperature (15°C, 40%RH) prior to moving to hotter conditions and exercise. Spraying artificial sweat caused a sudden spike in GSC (see Figure 6.5), suggesting the strong influence of sweat actually on the surface. When the skin was towel dried GSC decreased, but did not return to pre-spraying values. This may be associated with the absorption of moisture into the sweat glands and epidermis as discussed by Edelberg (1972). However, during a pilot study (see Appendix C), careful spraying of artificial sweat was done around the electrode so not to contaminate the conditions at the contact point of the electrode. Slight differences were found in GSC depending on the quantity and concentration of sodium chloride sprayed on the skin, however no significant differences in GSC_{raw} were found. The results of study 2 and that from the pilot test outlined in Appendix C suggest that GSC is only influenced by sweat on the skin surface that is in direct contact with the electrode point. The amount of sweat and its concentration between the electrodes will have no influence on GSC, but what comes into contact with the electrode will. The extent to which the quantity and concentration will affect GSC remains unknown and requires further investigation.

6.4.3 Standardisation of GSC

Study 2 aimed to determine the most appropriate method of standardising GSC due to the variability in the data between and within individual’s values. This variability prevents the possibility of calibrating GSC instruments and increases the sources of error that are most likely associated with different number of active sweat glands, sweat output per gland, sweat composition and the influence of other bodily fluids in the measurement area. The results revealed that all forms of standardisation were highly correlated with the physiological responses (T_c, T_b and $\bar{T}_{sk}$) and no single standardised form proved to have the strongest relationship. Overall, ∆GSC also had strong correlations with the majority of the measurements, but small differences exist between the r^2 values with other standardisations. It may be more informative to consider the standard deviations (SD's) for each type of standardisation. The result showed that GSC_{raw} had the largest SD's throughout the trial and at each location. GSC_{std} displayed the smallest SD, followed by ∆GSC which suggests smaller variation in the data collected. For all forms of standardisation, SD is generally higher during exercise when GSC was high. The reason as to why GSC_{std} had the lowest SD is due to the type of standardisation as it is relative to each individual's minimum and maximum values. Lykken and Venables (1971) claimed that this type of standardisation reduces the variations in the value, allowing it to be proportional to the individual being tested. In this statement they have highlighted a problem for thermoregulatory research. By using this technique, you risk losing information regarding local variation caused by the differing number of sweat glands or the sweat output per gland across the body. This raises the question as to whether it is important to be able to compare locations across the body. For example, the upper back and arms are high and low sweat producing areas respectively (Smith and Havenith, 2011), but measuring GSC from these areas and standardising relative to their minimum and maximum values would suggest a fully wet area in both locations despite a differing sweat output. Lykken and Venables (1971) claimed that if you can obtain a good estimate of the absolute maximum and absolute minimum, then you could partial out extraneous sources of variation in the measurement. The magnitude of this error discussed by Lykken and Venables (1971) are associated with psychophysiological research and are likely to be much lower than measurements related to thermophysiological research when sweat production is markedly higher. Therefore uncertainties exist in this test, and that of future tests, as to whether a true absolute minimum and absolute maximum has actually been achieved and whether this is suitable for thermoregulatory type research.

The assessment of skin blood flow using Laser Doppler flow technique also requires a maximum value for standardisation and the data is expressed as a percentage of the maximum. The ability to obtain a maximum skin blood flow response is presumed when the skin is locally heated and vasodilatation occurs. However, maximum skin blood flow is confirmed by a plateau in the data which is difficult to achieve for GSC and was not obtained in any of the studies in this chapter. $GSC_{\%max}$ was calculated relative to the highest GSC value achieved. As the aim of the investigation was to determine the maximum GSC for each site of measurement, the values produced should be relative to each individual. However, large SD's were produced (see Figure 6.5), indicating that the data points are spread over a large range of values. This form of standardisation is suitable for some test designs but not all. For example comparing values during a repeated measures design whereby individuals' GSC is compared during the same test condition is plausible. However it will not be as effective when assessing individuals during different test conditions. For example, during an exercise test in neutral climatic conditions maximum GSC would be very different to that produced in hot conditions. However, if the values were expressed as a percentage of the maximum for each test, then results indicating 50% might actually correspond to two very different sweating values. This may be practical for single test measurements, or determining variability between individuals in the same conditions, but to be able to compare results using $GSC_{\%max}$ becomes problematic. The only foreseeable way around this problem is to have a standardised pre-test whereby the maximum value is determined for each individual and this value is used regardless of whether the individual reaches this value during a separate test condition. This study attempted to attain a maximum by exposure to hot conditions and spraying artificial sweat on the skin under the contact point of the electrode. However, due to the limited effect of sprayed sweat, this does not confirm that a maximum value is achieved. Stimulating the sweat glands was considered, but pilot testing confirmed that iontophoresis needed to do this interferes with the measurement of GSC. A maximum value may be achieved in conditions of hidromeiosis, but this requires additional testing that, according to research by Candas et al. (1980), may take up to 90 minutes to achieve. Whether such tests are feasible and practical for each study is questionable.

The literature surrounding the topic of electrodermal properties is largely based on psychophysiological studies. Expressing GSC as a change from baseline is important when assessing response to psychological stimuli as an individual's level of alertness/arousal will vary and ultimately influence the initial GSC values. It would be natural to expect different levels of response for individuals of different levels of alertness and arousal. In terms of physiological responses, GSC is correlated linearly (r^2=0.89) with increasing and decreasing number of active sweat glands, as found by Thomas and Korr (1957). This supports why the ΔGSC also had a strong relationship. However, large intra-individual variations may cause different baseline values for a given test. ∆GSC has been previously reported by Machado-Moreira et al. (2009) in a study on the thermal and psychological changes associated with sweating. The inability to obtain a true maximum GSC may explain why they deemed it necessary to report GSC as a ∆GSC.

The place of application of the electrodes and the differing GSC levels might just be a factor of individual variation of sweat gland density, sweat gland activity and sweat composition, all of which are known to vary within and between individuals (Sato and Sato, 1983; Patterson et al. 2001). The values of minimum and maximum GSC will be a function of the measuring site (i.e. sweat gland density, sweat gland activity and sweat composition). As a result a standardised form for each site and for each individual should be used to cancel out this effect. Due to the uncertainty of obtaining a true maximum and the impracticality of exposing participants to additional conditions to augment the sweat glands to their maximum, ∆GSC is proposed as the chosen form of standardisation for future tests. The smaller SD for ∆GSC and the strong correlations with all the physiological response justify the use of ∆GSC. However, it is imperative that a reliable minimum GSC value is obtained to reduce any sources of error in its estimation. Minimum values should be determined with a pre-exposure measurement whereby a participant is exposed to a cold room (<20°C) and required to rest during which individual areas of GSC are measured. The participant is then permitted to complete the main trial. This technique aims to provide a standardised protocol (to be used) which would permit data to be compared across different investigations regardless of test conditions. The proposed method in this report is by no means the gold standard method, but it provides guidelines which can be adhered to in future research. More investigations are required to confirm this standard protocol and the method of expressing GSC.

6.5 Conclusion

This study aimed to assess the reliability, validity and reproducibility of GSC and propose a method of how to standardise it. The following conclusions were drawn.

- Strong correlations existed between GSC (of all standardised forms) between two identical tests, however significant differences occurred between some of the values. This indicates that the response of GSC to an exact protocol will be consistent but the actual values collected will be different.
- Standardising GSC reduces the errors in the measurement.

- Regardless of standardisation, GSC had a strong correlation with T_c, T_b and mean T_{sk}, RSR and w_{local}, indicating that it can be used in thermoregulatory research and the measure is related to the amount of sweat produced.
- GSC is a valid measure of sudomotor activity but should be confirmed with a larger sample size and ideally against ventilated capsule method to monitor a time response of sweat gland activity and output.
- RSR quickly declines post exercise, which is not mirrored by GSC. This may be associated with sweat remaining within the glands and skin and the inability of sweat to evaporate from the contact point of the electrode.
- GSC is not influenced by the quantity of sweat on the skin surface, but it is affected by the sweat directly underneath the contact area of the electrode.
- GSC_{std} have the lowest standard deviation and GSC_{raw} had the highest. Standard deviations were higher when sweat production was high.
- Reservations exist over whether a maximum GSC can ever reliably be achieved.
- A maximum value may be achieved in conditions of hidromeiosis but this requires time consuming additional testing that may be unfeasible and impractical for future research.
- Due to the uncertainty of obtaining a true maximum and the impracticality of exposing participants to additional conditions to augment the sweat glands to their maximum, ∆GSC is proposed as the chosen form of standardisation for future tests.
- The smaller SD for ∆GSC and the strong correlations with all the physiological response justify the use of ∆GSC.
- It is imperative that a minimum GSC value is obtained to reduce any sources of error in its estimation.
- Minimum values should be determined with a pre-exposure measurement whereby a participant is exposed to a cold room (<18°C) and required to rest during which individual areas of GSC are measured. The participant is then permitted to complete the main trial and GSC calculated as a change from baseline.

Chapter seven – Laboratory study 4

A comparison of skin wettedness and galvanic skin conductance as predictor of thermal comfort and wetness sensation during different exercise intensities

7 Chapter Summary

The ability of local skin wettedness (w_{local}) and galvanic skin conductance (GSC) to predict local thermal comfort during two different exercise intensities was compared in 9 males. In a balanced order, participants exercised at a fixed speed (4.5 km·hr^{-1}; ~20% $\dot{V}O_{2max}$ for 45 minutes (WALK) (29.0 ± 1.9°C, 29.8 ± 3.6% RH) in one test and in a separate test exercised at 70% $\dot{V}O_{2max}$ for 45 minutes (RUN) (26.2 ± 2.1°C, 31.1 ± 7.0 % RH). During both tests w_{local}, change from baseline GSC (ΔGSC) and local thermal comfort was recorded and averaged every 5 minutes. The relationship between perceptual responses and the physiological responses during high and low sweat production was investigated. The results suggest that both w_{local} and ΔGSC are strong predictors of thermal comfort during the WALK when sweat production was low and thermal discomfort minimal ($r^2>0.78$ and $r^2>0.80$, respectively. As expected, w_{local} reached ceiling values due to high sweat production during the RUN, whilst ΔGSC gradually increased throughout the experiment. Thermal comfort had a stronger relationship with ΔGSC than w_{local} during the RUN ($r^2>0.95$ and $r^2>0.75$, respectively). When metabolic heat production and thus sweat production are high, ΔGSC should be used to predict thermal comfort and not w_{local}. Unlike Chapter 5, the body sites were not manipulated to control w_{local} but allowed to vary naturally over time and local thermal comfort limits were indentified. According to w_{local} data, regional differences in thermal comfort limit exists, which suggests that the extremities are more sensitive than areas of the torso. These values oppose the findings of Chapter 5, where the arms were found to be the least sensitive. This is explained with a model of segmental interaction; the torso will naturally produce more sweat than the extremities at all times and the thermal comfort of areas with low w_{local} appear to be more affected by other wetter areas. Thermal comfort limits can be determined using w_{local}, yet ΔGSC cannot and suggests that the maximum discomfort experienced is relative to the amount of sweat produced by each body site.

7.1 Introduction

The influence of local and whole body skin wettedness (w_{body}) on thermal comfort has been well reported in the literature (Winslow et al. 1939; Gagge et al. 1969a; Nishi and Gagge, 1977; Fukazawa and Havenith, 2009; Umbach, 1982). Research has investigated regional differences in sensitivity to w_{local} using specialised clothing garments comprised of impermeable and permeable material to manipulate w_{local} (Fukazawa and Havenith, 2009; Umbach, 1982; Chapter 5 of the this thesis). This required a special methodology to attain the right balance of w_{local} of the target and non-target areas. The level of discomfort experienced in these experiments was minimal as the main aim was focused upon the transition from a comfortable to an uncomfortable state. Higher levels of thermal discomfort have rarely been explored and neither has its relationship with w_{local}. In order to achieve more severe discomfort scores, the heat strain needs increasing, either through changes in ambient conditions, clothing and/or metabolic rate. However, using the same technique as Chapter 5, changing either of these parameters would be impractical due to the difficulty in controlling the contrasts in w_{local} and local thermal comfort across all regions. Although this technique is useful for determining regional sensitivity, in working environments the natural distribution of sweat production and skin temperature (T_{sk}) will emerge. To provide clothing manufacturers with information on regional sensitivity to w with ecological validity, it would be more appropriate to assess the natural distribution of physiological and perceptual responses. Lee et al. (2011) recently developed a quantitative and qualitative method based on subjective perceptions to predict locally wet skin in uniform clothing. Participants took part in a rest – exercise protocol whilst wearing three different clothing ensembles of differing insulation and evaporative heat resistances. During each condition a body map was presented every 10 minutes and participants marked areas on the body that felt wet due to sweat. The areas initially marked were the ‘first perceived wetted region’ and the most frequently marked regions were named the ‘most wetted region’. They investigated 21 body sites and the chest, forehead and upper back were most frequently reported as the first wetted region. They may be defined as sensitive areas, but these areas match those known to produce large volumes of sweat in comparison to other locations (Smith and Havenith, 2011, 2012). The transition away from comfortable and dry used in Chapter 5 can be compared to the first wetted regions noted by Lee et al. (2011). The findings do not match those of Chapter 5, which can be explained by the differing methodologies employed. Lee et al. (2011) investigated perceptual responses in a natural condition, where physiological mechanisms responded naturally and perceptual responses followed suit. The perceptual responses were not rated using a Likert scale or visual analogue scale but rather indicate (with a tick) next to a designated body part that felt wet. As a result, they were unable to establish the degree of wetness experienced, which may vary across the body. Alongside this, perceived skin wettedness was estimated based on perceptual responses and body surface area, whilst w_{local} was estimated by rational indices using heat transfer equations based on T_{sk} and clothing properties (Parsons, 2003). Lee et al. (2011) found moderate, significant relationships between perceived skin wettedness and actual skin wettedness at rest ($r^2=0.41$, $p<0.01$). The manipulation studies carried out in Chapter 5 and by Fukazawa and Havenith (2009) and Umbach (1982) measured w_{local} using humidity sensors at each location and were therefore better equipped at providing quantitative results. By controlling w_{local}, these studies identified areas that will likely cause the most local and whole body discomfort and at what levels of w_{local} this will occur. However, they also artificially increased w_{local} beyond what may actually happen, particularly at the extremities. Therefore, it would be interesting to determine whether the regional sensitivity observed in the Chapter 5 would still produce similar patterns in a natural setting.

Lee et al. (2011) reported the diminishing role of w during heavy sweating and claimed that perceived skin wettedness was valid for predicting thermal discomfort during rest or light intensity exercise rather than conditions where sweat production is high. In such conditions w_{local} is likely to reach ceiling values. Doherty and Arens, (1988) also noted a reduced ability to predict w at higher metabolic rates and thus for predicting thermal comfort. Therefore, if thermal discomfort increases an alternative measurement must be sought to aid the prediction. It has previously been stated that the epidermis swells due to the presence of sweat, which increases receptors sensitivity within the skin (Berglund and Cunningham, 1986; Berglund, 1995, cited in Arens and Zhang, 2006, p.595). Therefore a parameter that indicates sweat gland activity, skin hydration and surface sweat may provide more sensitive data regarding perceptual responses. The measurement chosen for investigation is GSC, which was previously investigated for its reproducibility, reliability and validity in Chapter 6. If GSC can provide information regarding the hydration status of the epidermis then more sensitive data may be obtained regarding various degrees of thermal comfort during higher sweat rates.

7.1.2 Aims

The aim of this experiment is explore the relationship between local thermal comfort and w_{local} during two different exercise intensities without manipulating regional body sites. This will provide information about the natural response of both physiological and perceptual responses and indicate sensitive areas. These results will be compared to those in Chapter 5 to determine whether any similarities exist between the two data sets.

Two exercise intensities will be employed which aim to produce situations where sweat production differs whilst still increasing the thermal discomfort experienced. It is expected that during high intensity exercise, w_{local} will reach its limit. Therefore an additional measurement (GSC) will be investigated to determine whether it improves the prediction of thermal comfort at higher metabolic rates. To further the research carried out in Chapter 5, the link between wetness sensation and w_{local} (and ΔGSC) will also be explored.

7.2 Methods

The experimental methodology is outlined in Chapter 3; however the pre-test session measuring anthropometrics (skin fold analysis) was not carried out. A summary with specific details to this experiment will be described here.

7.2.1 Participants

Ten British males (height 182.1 ± 7.5 cm, body mass 74.8 ± 8.5 kg, age 23.0 ± 2.8 yrs, $\dot{V}O_{2\text{max}}$ 52.9 ± 5.2 ml·kg·min^{-1}) were recruited from the staff and student population of Loughborough University.

7.2.2 Experimental design

The aim of the investigation was to monitor the physiological responses including local skin wettedness (w_{local}), skin temperature (T_{sk}), core temperature (T_{c}), body temperature (T_{b}) and galvanic skin conductance (change from baseline) (ΔGSC) with the following perceptual responses; namely thermal comfort and wetness sensation. These relationships were investigated during two different exercise intensities without manipulating w_{local} as done in the Chapter 5. The experiment was designed to have two clear distinguishable conditions that would impose different heat stresses on the participants and thus result in different sweat responses and perceptual responses. Alongside this, each condition was designed to cause sufficient levels of discomfort.

For this purpose, each participant completed a pre-test session to assess fitness level and two main trials on separate days in a balanced order. The experiment was treated as a repeated measures design. The pre-test session and main experimental trials are detailed below.

7.2.3 Pilot study

Pilot studies were carried out in order to determine appropriate exercise intensities and environmental conditions that would fulfil the aims of the investigation. For comparison of results with Chapter 5, and in line with previous research in this area by Fukazawa and Havenith (2009), an exercise intensity was chosen for condition one (WALK) which corresponded to a walking speed of 4.5 km·h^{-1} (an approximate metabolic heat production of 146 W·m^{-2} and 20% $\dot{V}O_{2max}$). The exercise intensity for the second condition was selected at 70% $\dot{V}O_{2max}$ which was relative to the individual's fitness status. This corresponded to an average metabolic heat production of 508 W·m^{-2}. Ideally the same ambient conditions would have been chosen for each condition, but during pilot tests it became apparent that they needed to be slightly different. Firstly, in order to achieve higher discomfort ratings in both exercise conditions the ambient condition during the WALK needed to exceed >25°C. However, an ambient condition greater than 25°C during the RUN frequently caused sensors to fall from the skin due to excess sweat and thus lost data. Following this, environmental conditions were decided based upon information gained from calculating required sweat rate (SW_{req}) (ISO 7933, 2004). Sw_{req} is derived from the 6 basic parameters; air temperature (T_a), radiant temperature (T_r), relative humidity (RH), air velocity (v), clothing insulation (Rcl), metabolic rate (M) and external work. From these values evaporation required (E_{req}) can be calculated using the following equation:

$$E_{req} = M - W - C_{res} - E_{res} - C - R$$

Where:

E_{req}	required sweat rate to maintain thermal balance (W·m^2)
M	metabolic rate (W·m^2)
W	mechanical work (W·m^2)
C	heat exchange on the skin by convection (W·m^2)
R	heat exchange on the skin by radiation (W·m^2)
E_{res}	respiratory heat exchange by evaporation (W·m^2)

C_{res} respiratory heat exchange by convection (W·m^2)

From this calculation and knowledge of the maximum evaporation (E_{max}) possible for the environmental conditions, and the sweating efficiency (*r*), the following can be calculated:

$$w_{req} = \frac{E_{req}}{E_{max}}$$

Where w_{req} is the required skin wettedness

$$S_{req} = \frac{E_{req}}{r}$$

Where S_{req} is the required sweat rate

Where *r* is calculated using the following:

$$r = \frac{1 - w^2}{2}$$

Table 7.1 indicates the environmental conditions and corresponding S_{req} for condition one (WALK) and condition two (RUN). Table 7.1 confirms that the test conditions will expose participants to a moderate to high degree of heat strain, causing substantial sweating that will differ for each condition and potentially differing degrees of discomfort. Pilot tests confirmed that the environmental conditions were at a level where substantial data would not be lost through sensors falling of the skin due to complete saturation of the skin with sweat.

Table 7.1: The ambient temperature (T_a), radiant temperature (T_r), relative humidity (*RH*), air velocity (*v*), intrinsic thermal insulation of clothing (Rcl) and the metabolic rate (M) for the WALK and RUN. Using these variables, the required sweat rate (SW_{req}) and required skin wettedness (w_{req}) was estimated for the WALK and RUN.

	WALK	RUN
T_a (°C)	30°C	25°C
T_r (°C)	30°C	25°C
RH (%)	30%	30%
v (ms^{-1})	0	0
Rcl (m^2 k·Pa·W^{-1})	0.03	0.03
M (Wm^{-2})	146	508
S_{req} (W·m^{-2})	**141.6**	**781.3**
S_{req}(l·hr^{-1})	**0.3**	**2.1**
w_{req}	**0.76**	**>1.00**

7.2.4 Clothing

Participants' wore a 100% polyester long sleeve top and trouser ensemble with a high permeability for heat and vapour transfer (thermal resistance of 0.154 $m^2 \cdot K \cdot W^{-1}$ and water vapour resistance of 35.9 $m^2 \cdot Pa \cdot W^{-1}$) tested on a thermal manikin (Newton, Measurement Technology Northwest, USA). The clothing was loose fitting across the body. Participants wore their own socks and athletic trainers.

7.2.5 Methodology

During the first visit, participants' stature and body mass were recorded followed by a submaximal fitness test based on the Åstrand-Rhyming method (ACSM, 2006), as outlined in Chapter 3.

For the main trial, pre and post test nude weight were recorded. Participants self inserted a rectal probe 10 cm beyond the anal sphincter and dressed in the required clothing. Eight skin thermistors (Grant Instrument Ltd, Cambridge, UK) were attached to the skin using 3M^{TM} Transpore^{TM} surgical tape, (3M United Kingdom PLC). Eight humidity sensors (MSR electronics GmbH, Switzerland) were fixed to a holder and glued to the skin using Collodion U.S.P (Mavidon Medical Products, USA) to measure w_{local} (as described in Chapter 3). The sensors were attached to the skin at the following locations; chest, abdomen, scapula, lower back, upper arm, forearm, thigh and calf). Four pre-gelled electrodes were attached to the chest, upper back, upper arm and upper leg for the measurement of ΔGSC using MP35 Biopac Systems (Goleta, California, USA). Once fully equipped the participant sat in a thermoneutral environment (19.8 ± 1.6°C, 40.6 ± 4.1% RH) for 15 minutes to allow physiological responses to stabilise. During rest, participants were familiarised with the sensation scales and allowed to practise rating their sensations. Following the rest period, participants entered the environmental chamber where they began one of the exercise protocols. The WALK protocol require participants to walk for 45 minutes at ~20% $\dot{V}O_{2max}$ (4.5 $km \cdot hr^{-1}$) in a chamber at 29.0 ± 1.9°C, 29.8 ± 3.6% RH, with no wind. The RUN protocol required participants to walk at 4.5 $km \cdot hr^{-1}$ for 5 minutes, followed immediately by a run at 70% $\dot{V}O_{2max}$ for 40 minutes in a chamber at 26.2 ± 2.1°C, 31.1 ± 7.0 % RH, with no wind. The first 5 minutes of low exercise intensity during the RUN was to allow participants to warm up and prepare the wires and equipment prior to running.

7.2.6 Perceptual responses

Perceptual responses are shown in Table 7.2 to measure, wetness sensation (WS) and thermal comfort (TC). Participants were introduced to the sensation scales and instructed how to interpret them and score. They scored each sensation for their whole body and each local body region (chest, abdomen upper back, lower back, upper arms, lower arms, upper legs and lower legs) during the last 5 minutes of rest and at 5 minute intervals during exercise. As carried out in Chapter 5, the thresholds for when the skin no longer feels comfortable or dry will be defined as the w_{local} that corresponds with a comfort vote of -1 and a wetness vote of 1. These values will be used to define the sensitivity of localised zones to w_{local} and w_{body}.

Table 7.2: The perceptual scales used in this study to measure wetness sensation and thermal comfort.

Please state how wet your skin feels:	**Do you find this:**
0 Dry	0 Comfortable
1	-1
2 Moist	-2 Slightly uncomfortable
3	-3
4 Wet	-4 Uncomfortable
5	-5
6 Dripping wet	-6 Very uncomfortable

7.2.7 Data analysis

Statistical analysis was conducted using Statistical Package (SPSS) version 18.0. Analysis of the main effect of condition, location and time were analysed using three-way repeated measures ANOVA. Post hoc comparisons using Bonferroni correction were performed to analyse individual differences. In some instances, differences between conditions were analysed using paired samples t-test and corrected for multiple comparisons. Correlation analysis was performed to assess the relationship between perceptual and physiological responses. Multiple regression analysis was used to determine the best predictors of perceptual responses for the two conditions. Unless otherwise stated, all measurements are presented as means with standard deviations (± S.D) and significance is defined as $p<0.05$.

7.3 Results

7.3.1 Participants

Participant 7 was deemed as a ‘non responder’ as local and whole body thermal comfort was maintained throughout each test and was subsequently removed from the analysis. All data is expressed without participant 7.

7.3.2 Experimental design

No significant differences were found in T_c in the rest phase between the WALK (37.0 ± 0.3°C) and RUN condition (37.1 ± 0.3°C) ($p>0.05$). However, the increase in T_c from baseline to the end of the experiment was significantly less for the WALK (37.2 ± 0.3°C) than the RUN (38.1 ± 0.4°C, $p<0.001$). Alongside this, GSL was significantly higher at the end of RUN compared to the WALK (516 ± 132 and 271 ± 90 $g{\cdot}m^{-2}{\cdot}hr^{-1}$, respectively, $p<0.001$).

Figure 7.1a-c shows the mean values at the end of each condition (WALK and RUN) for w_{local}, ΔGSC and local T_{sk}. Although not shown in the Figure 7.1 w_{local} continued to increase during the WALK but a ceiling effect was observed during the RUN. This typically occurred >0.60. On the other hand ΔGSC continually increased during both conditions. According to three way repeated measures ANOVA, there was a significant overall effect of condition on w_{local} and ΔGSC ($p<0.05$) but no effect on local T_{sk} as it was similar between conditions. A significant effect of time was found on all three parameters as they increased from rest to the end of exercise. A significant effect of location was found for w_{local} and T_{sk} but not ΔGSC. Results from the pairwise comparison (with and without Bonferroni corrections) are highlighted in Table 7.3. Overall the torso was significantly higher than the extremities.

***Main findings**:*

- all physiological responses were higher at the end of the RUN compared to the WALK;
- Overall, areas of the torso had higher w_{local}, ΔGSC and T_{sk} than the extremities.

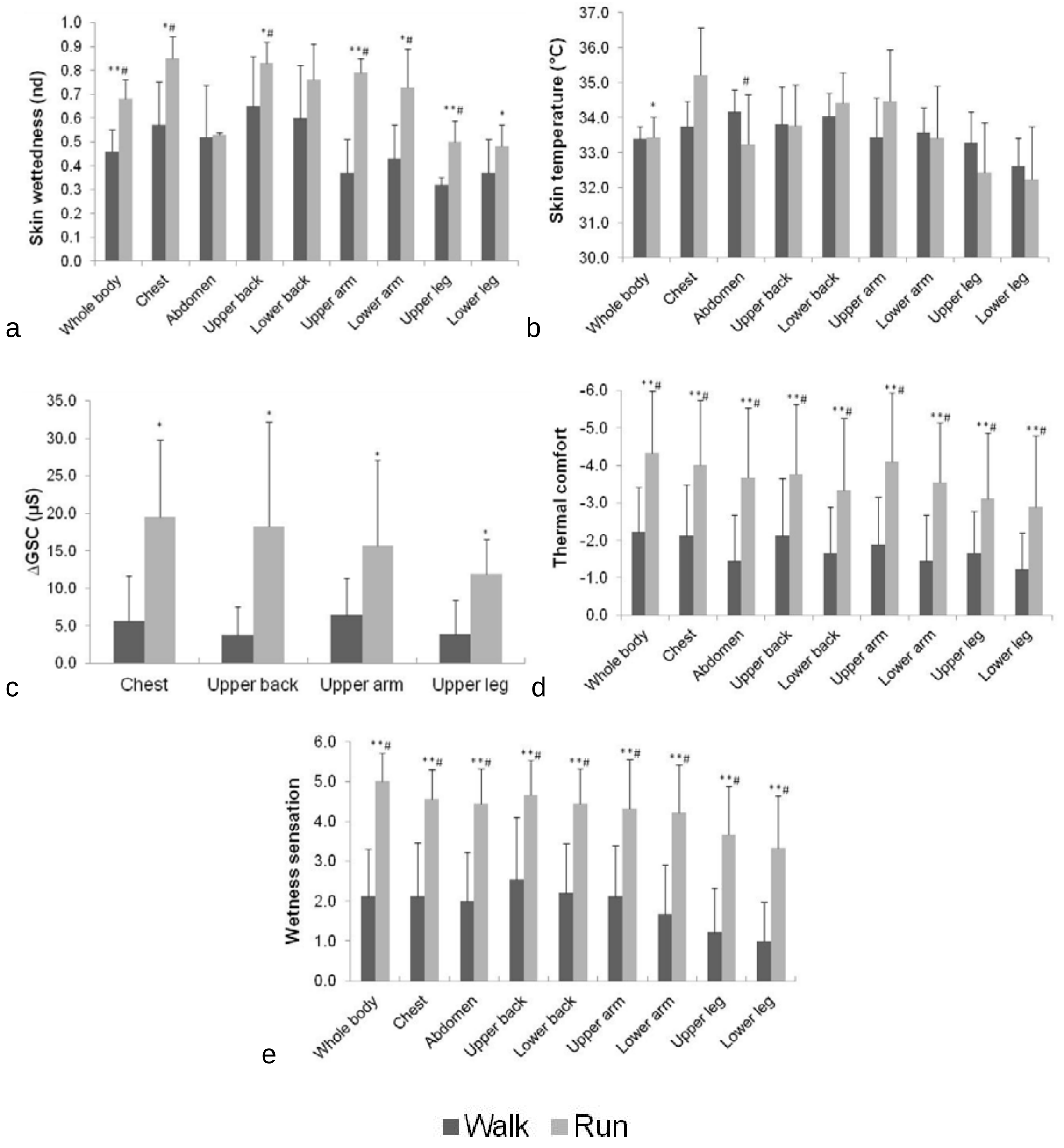


Figure 7.1: Males (n=9) **m**ean values (±SD) of a)w_{local},b) ∆GSC, c) T_{sk}, d) thermal comfort and e) wetness sensation measured at the end of the WALK and RUN. Significant differences between WALK and RUN is denoted by * ($p<0.05$) and ** ($p<0.001$) (without corrections) and by # $p<0.05$ (with Bonferroni adjustment).

7.3.3 The relationship between thermal comfort and physiological variables

The graphs displayed in Figure 7.2 and Figure 7.3 illustrate the relationships between local thermal comfort and w_{local} and ΔGSC (respectively) during the WALK and the RUN. The strength of the relationships (r^2) between each variable and thermal comfort are displayed in Table 7.4. During the WALK, a strong linear relationship exists between local thermal comfort and w_{local} at all locations ($r^2>0.78$). During the RUN, local thermal comfort has an exponential relationship with w_{local} due to the ceiling effect

Table 7.3: Significance of pairwise comparison between locations for w_{local} (▨ $p<0.05$, with Bonferroni corrections ($\$p<0.05$ and $\$\$p<0.001$ without corrections), for T_{sk} ($*p<0.05$ with Bonferroni corrections ($\#p<0.05$ and $\#\#p<0.001$ without corrections). No significant differences were observed for ΔGSC.

	Whole body	Chest	Abdomen	Upper back	Lower back	Upper arms	Lower arms	Upper legs	Lower legs
Chest	#								
Abdomen									
U back									
L back		#							
U arms	$ ▨	$	$	$					
L arms		##	#	$#	#				
U legs	$#	$##*	$##*	$#*	$#	#	$		
L legs	$##*	$##*	$##*	$##*	$##*	#	$#	#	

in w_{local}; thus it was analysed using a non-linear relationship. Strong relationships were still found ($r^2>0.75$), but at most locations the relationship was weaker than the WALK (exception include abdomen, upper and lower legs). The relationship between thermal comfort and ΔGSC bore a curvilinear relationship primarily due to the initial data points collected (Figure 7.3). The data was analysed using an exponential relationship for both conditions. The strength of these relationships improves from the WALK ($r^2>0.80$) to the RUN ($r^2>0.93$) at each location. Skin temperature has a moderate to strong relationship with thermal comfort ($>0.37\ r^2<0.95$) and the strength of these relationship generally improved from the WALK to the RUN.

Observing the data in Figure 7.2 and Figure 7.3, there is an overlap of data points from the WALK and RUN. Therefore, multiple regression analysis was performed on the combined data of both conditions. The relationship between thermal comfort and w_{local} during the RUN was transformed exponentially and then combined with data from the WALK. The ΔGSC data was also transformed using the square root function. Stepwise multiple regression was performed on whole body thermal comfort with the following physiological responses, $\bar{T}_{sk}$, w_{body} and T_c. In Table 7.5 and Table 7.6, models that best predict thermal comfort are highlighted in grey. To allow for comparison and indicate the effect of each predictor, individual predictors are entered into separate equations. Multiple regression analysis was performed on local thermal comfort using local T_{sk}, w_{local}, and ΔGSC as predictors. Due to the nature of the physiological variables measured in this investigation, collinearity amongst the predictors was observed. In such cases, a model which best predicted thermal comfort ($r^2>0.80$) using the minimum amount of predictors was opted for. Local and whole body thermal comfort can be determined using the regression equations indicated in grey in Table 7.5 and Table 7.6. The high, significant correlations observed from the data analysis revealed these equations are valid for conditions employed by this experiment.

Table 7.4: Individual relationship (r^2) between thermal comfort and ΔGSC, w_{local}, T_{sk}, and T_c. † Indicates non-linear correlation – indicates where analysis was not carried out.

		ΔGSC	w_{local}	Local T_{sk}	T_c
Whole body	Walk	-	0.96	0.75	0.56
	RUN	-	0.84†	0.94	0.89
Chest	Walk	0.89†	0.93	0.37	-
	RUN	0.97†	0.87†	0.96	-
Abdomen	Walk	-	0.93	0.68	-
	RUN	-	0.96†	0.55	-
Upper back	Walk	0.86†	0.98	0.50	-
	RUN	0.95†	0.97†	0.69	-
Lower back	Walk	-	0.93	0.69	-
	RUN	-	0.75†	0.95	-
Upper arm	Walk	0.84†	0.92	0.75	-
	RUN	0.93†	0.82†	0.93	-
Lower arm	Walk	-	0.96	0.66	-
	RUN	-	0.98†	0.92	-
Upper leg	Walk	0.84†	0.78	0.88	-
	RUN	0.95†	0.98†	0.78	-
Lower leg	Walk	-	0.80	0.92	-
	RUN	-	0.96†	0.82	-

Main findings:

- strong relationships were found between local thermal comfort and w_{local} ($r^2>0.75$) and ΔGSC ($r^2>0.84$);
- the strength of the relationship between thermal comfort and w_{local} generally declines from WALK to RUN, whereas it strengthens for ΔGSC;
- a ceiling effect is observed with w_{local} during high sweat production whilst ΔGSC continues to increase.

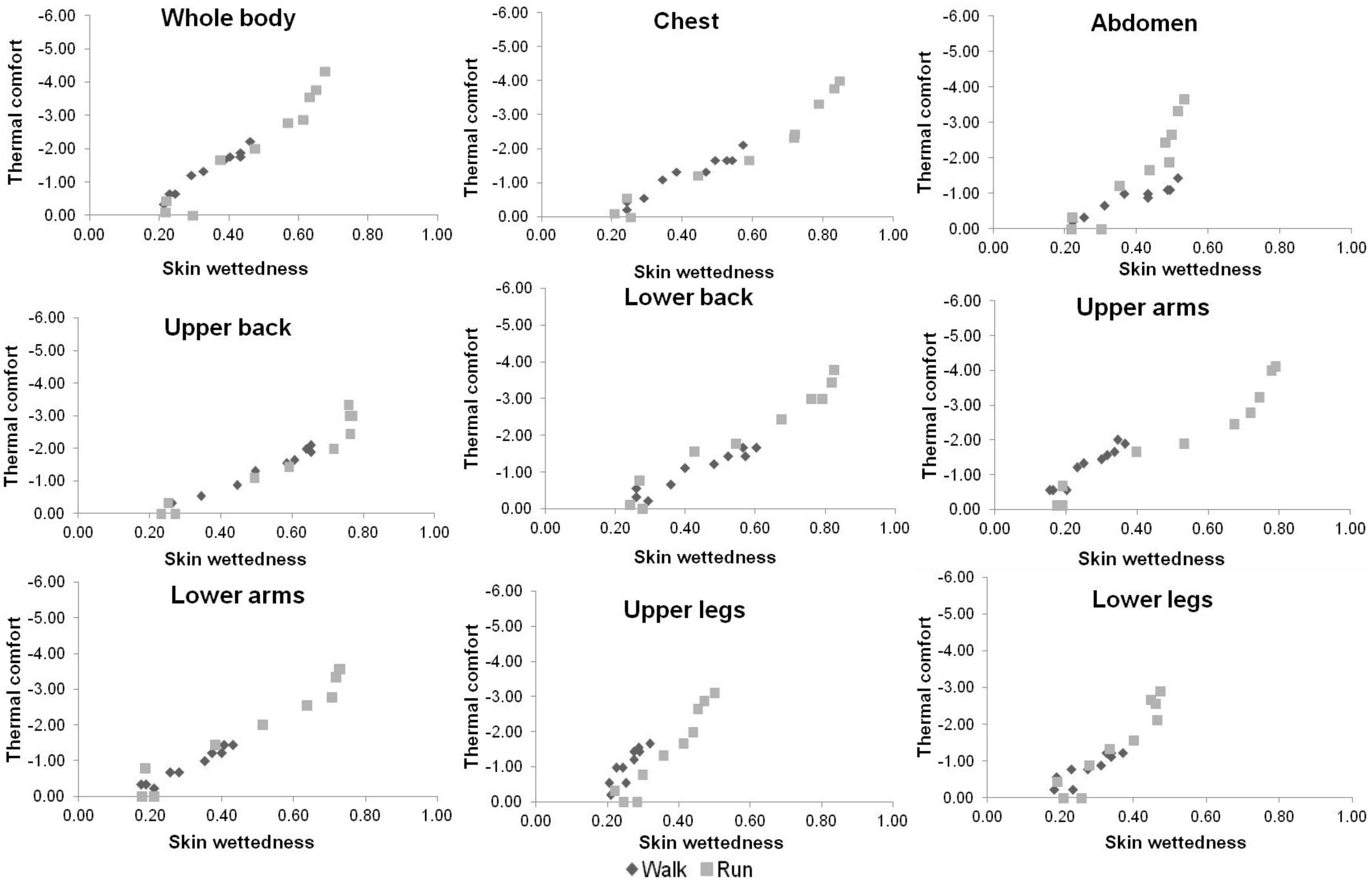


Figure 7.2: The relationship between local thermal comfort and w_{local} in both conditions (WALK and RUN), at each location.

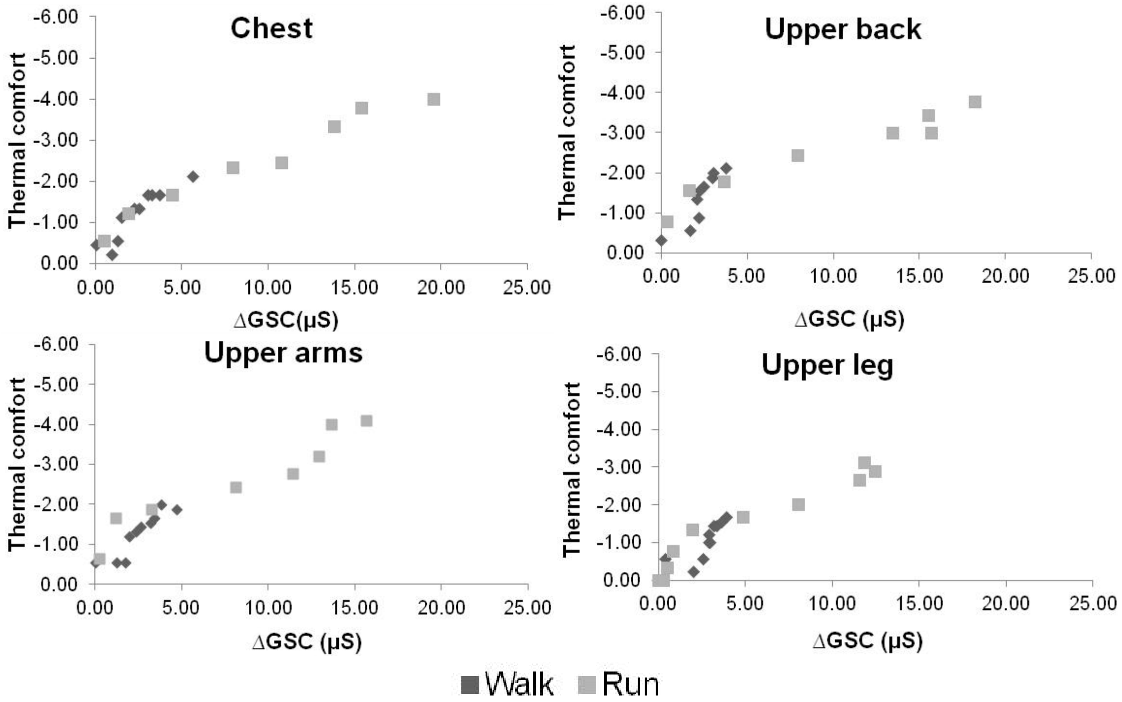


Figure 7.3: The relationship between local thermal comfort and ΔGSC in both conditions (WALK and RUN), at each location.

7.3.4 Regional difference in comfort perception

Local and whole body thermal comfort limits according to w_{local} are displayed in Figure 7.4. The comfort limits are defined as the point at which participants no longer feel comfortable (-1 vote). According to w_{local}, the values indicate that the upper legs and upper arms are the most sensitive during the WALK due to the lower w_{local} values (0.25 and 0.22, respectively). The lower back, upper back and abdomen are therefore classed as the least sensitive as they require higher w_{local} values before participants no longer felt comfortable (0.43). Despite all locations starting at similar w_{local}, the onset for discomfort occurs at a higher w_{local} during the RUN compared to the WALK; with the exception being the lower legs. The same principle was applied to ΔGSC and the results revealed the thermal comfort limits ranged between 1.6 and 2.8 µS during the WALK and 1.6 and 2.6 µS during the RUN. However the range of ΔGSC data (0.00 to 19.6 µS) over the course of the test is much wider than w_{local} (0.06-1.0) and therefore such small differences at the comfort limit may be meaningless.

The maximum discomfort scored at the end of each trial and the associated w_{local} and ΔGSC are presented in Figure 7.1d. As an alternative to looking at thresholds for sensation one could also consider areas with the highest discomfort at the end of exercise. During the WALK the chest and upper back scored the highest vote (>2.0),

Table 7.5: Regression equations for the prediction of male thermal comfort for the whole body and areas of the torso. The shaded boxes illustrate the best models to predict thermal comfort. The regression coefficients (B), their standard error (SE B), the standardised beta value (β) and the strength of the relationship (r^2) between thermal comfort and each predictor are shown (*p<0.05, **p<0.001).† indicates transformed data for w_{local} using exponential function and ‡ indicates transformed data for ΔGSC using square root function.

Location	Parameters	B	SE B	β	r^2	Location	Parameters	B	SE B	β	r^2
Whole body	Constant w_{body} † $\bar{T}_{sk}$	15.939 -4.314 -0.340	4.623 0.386 0.154	 -0.848 -0.168	0.95*	**Upper back**	Constant w_{local}† T_{sk}	-19.016 -3.302 0.685	6.280 0.176 0.190	 -1.051 0.202	0.964**
	Constant w_{body} †	5.753 -4.937	0.447 0.291	 -0.970	0.94**		Constant W_{local} †	3.580 -3.031	0.391 0.214	 -0.965	0.931**
	Constant $\bar{T}_{sk}$	50.474 -1.593	9.657 0.295	 -0.787	0.62**		Constant ΔGSC‡	-0.200 -0.803	0.171 0.072	 -0.945	0.893**
	Constant T_c	117.982 -3.214	14.553 0.391	 -0.889	0.79**		Constant T_{sk}	47.312 -1.457	19.486 0.580	 -0.509	0.260*
Chest	Constant w_{local} †	3.449 -3.040	0.296 0.170	 -0.976	0.95**	**Lower back**	Constant w_{local}†	3.658 -2.997	0.323 0.190	 -0.966	0.933**
	Constant ΔGSC‡	0.160 -0.927	0.128 0.055	 -0.973	0.95**		Constant T_{sk}	34.682 -1.086	4.617 0.139	 -0.879	0.772**
	Constant T_{sk}	51.362 -1.555	7.955 0.234	 -0.973	0.71**						
Abdomen	Constant w_{local}† T_{sk}	-13.304 -5.744 0.615	7.198 0.752 0.222	 -0.908 0.330	0.77**						
	Constant w_{local}†	6.459 -5.200	1.270 0.850	 -0.822	0.68**						

Table 7.6: Regression equations for the prediction of male thermal comfort for areas of the extremities. The shaded boxes illustrate the best models to predict thermal comfort. The regression coefficients (B), their standard error (SE B), the standardised beta value (β) and the strength of the relationship (r^2) between thermal comfort and each predictor are shown (*$p<0.05$, **$p<0.001$).† indicates transformed data for w_{local} using exponential function and ‡ indicates transformed data for ΔGSC using square root function.

Location	Parameters	B	SE B	β	r^2	Location	Parameters	B	SE B	β	r^2
Upper arm	Constant w_{local}† T_{sk}	18.471 -2.017 0.519	4.190 0.263 0.136	-0.687 -0.343	0.950**	**Lower leg**	Constant w_{local}†	7.127 -5.989	0.717 0.517	-0.939	0.882**
	Constant w_{local}†	2.466 -2.789	0.368 0.231	-0.949	0.901**		Constant T_{sk}	27.406 -0.897	5.146 0.162	-0.794	0.631**
	Constant ΔGSC‡	-0.023 0.934	0.181 0.080	-0.945	0.89**	**Upper leg**	Constant ΔGSC‡ w_{local}† T_{sk}	11.771 -0.368 -3.315 -0.243	3.443 0.130 0.709 0.095	-0.392 -0.484 -0.229	0.953**
	Constant T_{sk}	42.772 -1.346	5.204 0.157	-0.896	0.802**		Constant ΔGSC‡ w_{local}†	3.156 -0.620 -2.428	0.847 0.098 0.713	-0.659 -0.354	0.934**
Lower arm	Constant w_{local}†	3.991 -3.553	0.244 0.157	-0.983	0.966**		Constant w_{local}†	7.013 -6.041	1.053 0.764	-0.881	0.776**
	Constant T_{sk}	22.179 -0.772	9.366 0.286	-0.511	0.261*		Constant ΔGSC‡	0.297 -0.886	0.148 0.074	-0.942	0.888**
							Constant T_{sk}	22.339 -0.732	5.855 0.181	0.689	0.475**

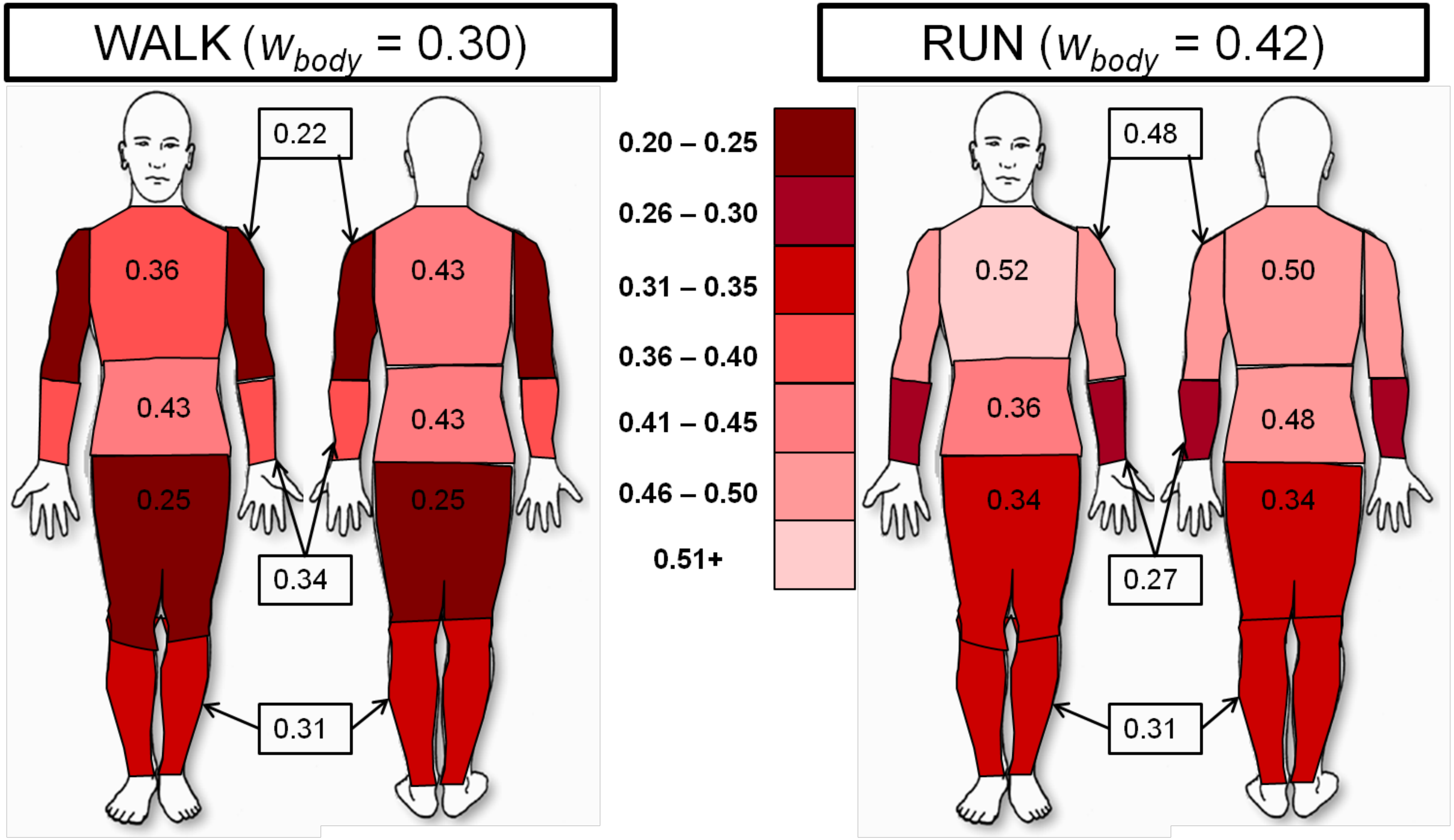


Figure 7.4: The w_{local} thermal comfort limits for each location during WALK and RUN, which corresponds to when locations no longer felt comfortable. The lower the number (in darker colours) indicates sensitive areas.

whilst the lower legs scored the lowest discomfort score (-1.2). The discomfort scores appear to be relative to w_{local} as these areas had the higher and lowest w_{local} values respectively. The only exception appears to be the upper arm during the WALK which has a similar discomfort score to the lower back (~-2.0) yet a much lower w_{local} (0.37 ± 0.14 vs. 0.65 ± 0.2). This response was mirrored by ∆GSC.

Main findings:

- the w_{local} thermal comfort limits suggest the extremities are more sensitive than the torso;
- ∆GSC suggest thermal comfort is relative to the amount of sweat produced; if so the torso will experience stronger discomfort than the extremities.

7.3.5 The relationship between wetness sensation and physiological variables

Figure 7.5 and Figure 7.6 illustrate the relationships between local wetness sensation and w_{local} and ∆GSC (respectively) during the WALK and the RUN. The strength of the relationships (r^2) between each variable and wetness sensation are displayed in Table 7.7. A similar pattern in observed between wetness sensation and w_{local} as seen with thermal comfort, in that during the WALK a linear relationship exists and during the

Table 7.7: The relationship between wetness sensation and ΔGSC, w_{local} and T_{sk} (r^2). † w_{local} transformed using exponential function, ‡ ∆GSC transformed using square root function.

		ΔGSC	w_{local}	Local T_{sk}
Whole body	Walk	-	0.98	0.95
	RUN	-	0.78†	0.69
Chest	Walk	0.76	0.97	0.32
	RUN	0.91‡	0.76†	0.96
Abdomen	Walk	-	0.97	0.51
	RUN	-	0.78†	0.57
Upper back	Walk	0.80	0.93	0.43
	RUN	0.96‡	0.97†	0.57
Lower back	Walk	-	0.95	0.81
	RUN	-	0.77†	0.93
Upper arm	Walk	0.85	0.95	0.69
	RUN	0.93‡	0.77†	0.93
Lower arm	Walk	-	0.91	0.65
	RUN	-	0.97†	0.93
Upper leg	Walk	0.40	0.87	0.77
	RUN	0.91‡	0.97†	0.59
Lower leg	Walk	-	0.90	0.70
	RUN	-	0.83†	0.71

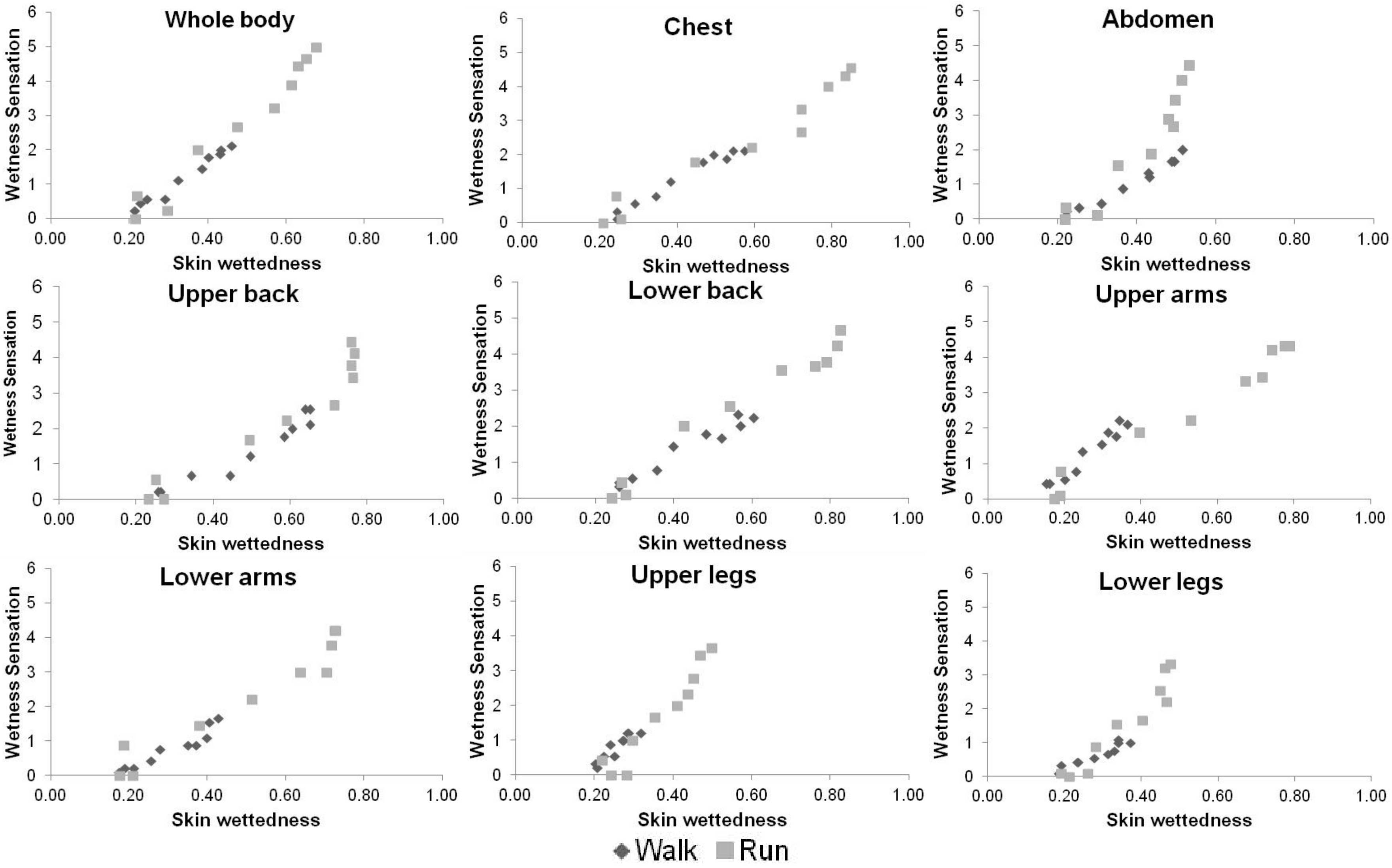


Figure 7.5: The relationship between local wetness sensation and w_{local} in both conditions (WALK and RUN), for the whole body and at each location.

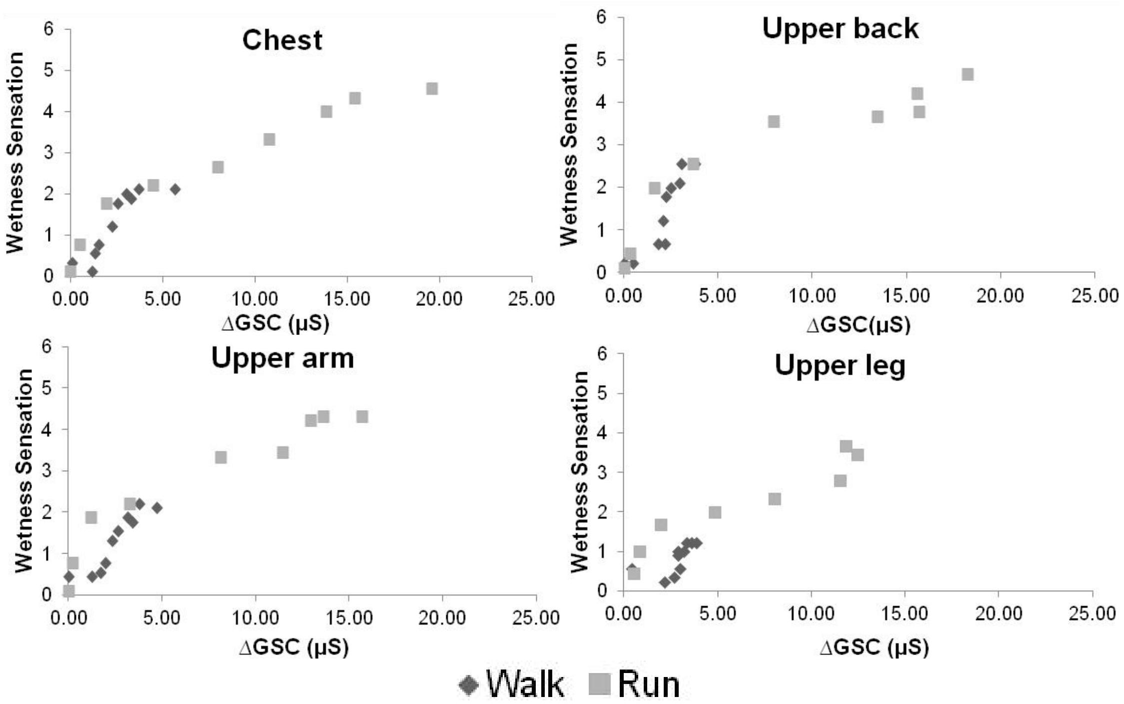


Figure 7.6: The relationship between local wetness sensation and ∆GSC in both conditions (WALK and RUN), at each location.

RUN an exponential relationship exists. A strong relationship was found between local wetness sensation and w_{local} at all locations in both conditions (r^2>0.76). At some locations, the relationship was stronger during the WALK than the RUN (whole body, chest, abdomen, lower back and lower leg). In comparison, the relationship between wetness sensation and ∆GSC improved for all locations during the RUN (r^2≥0.91) compared to the WALK (r^2≥0.40) (see Table 7.7). Local wetness sensation did not consistently have good relationships with local T_{sk}.

Main findings:

- moderate to strong relationships were found between local wetness sensation and w_{local} , ∆GSC and T_{sk} (r^2>0.40);
- the strength of the relationship between thermal comfort and w_{local} generally declines from WALK to RUN, whereas it strengthens for ∆GSC.

7.3.6 The relationship between perceptual responses

Strong linear relationships are found between thermal comfort and wetness sensation in both conditions (r^2>0.85). Figure 7.7 illustrate the strong linear relationship between thermal comfort and wetness sensation. During the WALK participants cross the

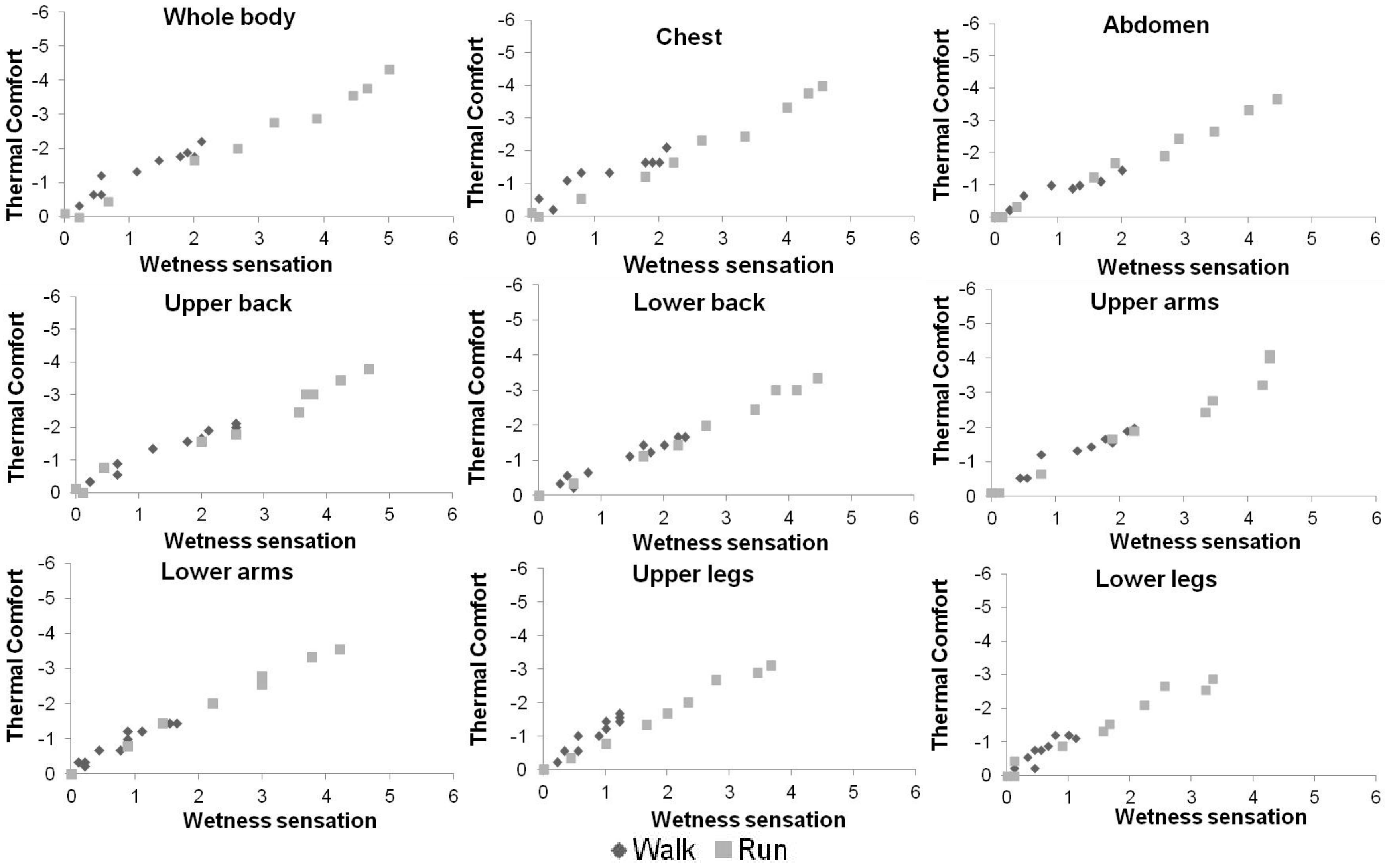


Figure 7.7: The relationship between local thermal comfort and local wetness sensation during both conditions (WALK and RUN) at each location.

comfort limit earlier than the wetness limit (i.e. they feel more discomfort before they detect moisture). However, during the RUN participants detect moisture (1 vote) before they no longer feel comfort (-1 vote). The abdomen, for example has a wetness sensation score of 1.5 (almost a moist sensation) when it became no longer comfortable (-1 vote). Alongside this, participants felt ‘wet’ (4 category vote) before they felt uncomfortable (-4 category vote).

Main findings:

- strong relationships were found between local thermal comfort and local wetness (r^2>0.85);
- the discomfort associated with a certain wetness level is lower in higher intensity exercise.

7.3.7 A comparison with chapter 5

In Chapter 5, regional w_{local} were manipulated in a controlled study whilst in the present study w_{local} varied naturally. The relationship between thermal comfort and w_{local} has been explored and data from the WALK condition will be compared to the results from Chapter 5 (see Figure 7.8). It should be noted that participants were not drawn from the same sample, but exercise intensity was similar (walking at 4.5 km·hr^{-1}). The graphs suggest that w_{body} and w_{local} at the torso follow a similar pattern during both tests as data points lie close together. However, data from Chapter 5 at the extremities shifts to the right in comparison to this study.

Table 7.8 indicates the comfort limits according to w_{body} and w_{local} for whole body and local thermal comfort respectively. The lower the comfort limit the more sensitive the area as it requires the least amount of sweat on the skin before it no longer feels comfortable. Overall, higher comfort limits were obtained in Chapter 5 than the WALK of the present study, suggesting more sweat is required locally to influence thermal comfort. According to Chapter 5, the lower back is the most sensitive (0.40) whilst the upper and lower arms are the least sensitive (0.57 and 0.65, respectively). However, according to the present study, the upper arms are the most sensitive (0.22). The comfort limits in Chapter 5 show more variation between zones whilst the values are more homogenous in the present study. The legs remain one of the most sensitive areas across all three conditions. Similar patterns are observed between the WALK and RUN, with the extremities being the most sensitive and the torso the least.

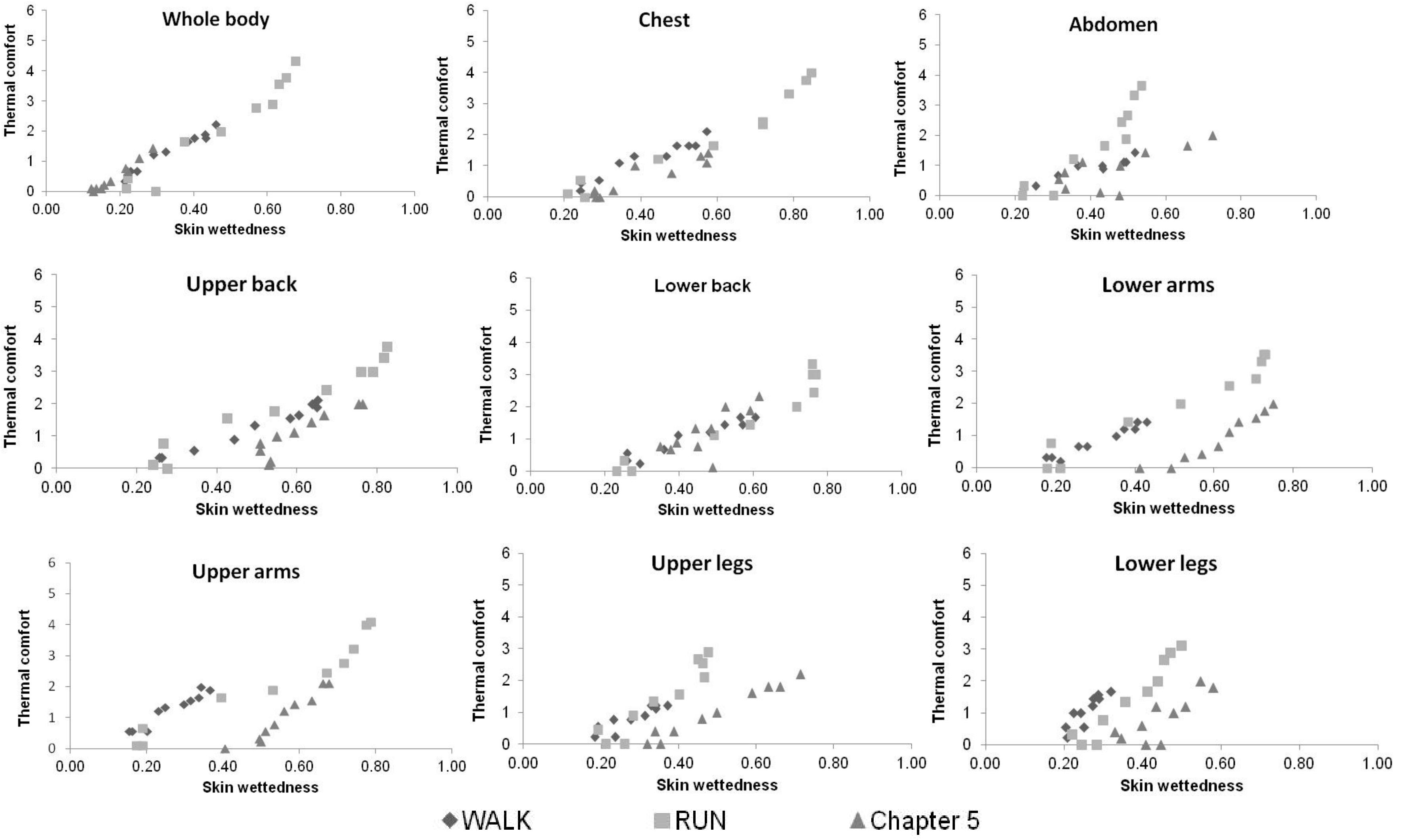


Figure 7.8: A comparison of data from chapter 5 and the present study (WALK and RUN) of the relationship between local thermal comfort and w_{local} for thw whole body and at each location.

Table 7.8: A comparison of local thermal comfort limits from chapter 5 and the present study during the WALK and RUN.

	Chapter 5	WALK	RUN
	Local comfort limit	Local comfort limit	Local comfort limit
Whole body	0.30	0.30	0.42
Chest	0.55	0.36	0.52
Abdomen	0.45	0.43	0.36
Upper back	0.56	0.43	0.50
Lower back	0.40	0.43	0.48
Upper arms	0.57	0.22	0.48
Lower arms	0.65	0.34	0.27
Upper legs	0.44	0.25	0.34
Lower legs	0.45	0.31	0.31

Main findings:

- lower comfort limits for w_{local} were obtained in the present study compared to Chapter 5;
- in comparison to Chapter 5, similar curves for the relationship between thermal comfort and w_{body} and w_{local} were observed for the whole body and the torso areas, whilst different curves existed for areas of the extremities.

7.4 Discussion

This chapter compared the ability of w_{local} and ΔGSC to predict local thermal comfort and wetness sensation during two different exercise intensities that stimulate different sweating responses. Regional differences in sensitivity to sweat were also explored using the two different variables. The main findings from this investigation were:

- at higher levels of sweating, a ceiling effect is observed with w_{local} whilst ΔGSC continued to increase with sweat levels;
- thermal comfort has a strong relationship with w_{local} and ΔGSC but the latter is stronger at higher metabolic rates as w_{local} levels off there;

- w_{local} suggests regional differences in the thermal comfort limit whilst ∆GSC does not and rather suggests that comfort is relative to the amount of sweat produced;
- there is a very strong link between thermal comfort and wetness sensation;
- lower comfort limits for w_{local} were obtained in the present study compared to Chapter 5 and regional differences were more homogenous.

These findings will be discussed in detail.

7.4.1 A comparison of w_{local} and ∆GSC in predicting thermal comfort during different exercise intensities

Past research has established the relationship between whole body thermal comfort and w_{body} and 0.30 has been defined as the thermal comfort limit (Winslow et al. 1939; Gagge et al 1969a; Nishi and Gagge, 1977). Research has moved forward by indentifying regional differences in thermal comfort to w_{local} (Fukazawa and Havenith, 2009; Umbach, 1982). However, the research has mainly focused upon the initial comfort limits for *w* and, since its introduction by Gagge (1937), researchers have reported the diminishing role of *w* during heavy sweating on the prediction of thermal comfort (Doherty and Arens, 1988; Lee et al. 2011). As a result, this study aimed to address the relationship between thermal comfort and *w* and introduce ∆GSC that could improve and/or aid the prediction of thermal comfort during high levels of sweat production. Figure 7.2 illustrates the linear relationship between local thermal comfort and w_{local} during the WALK and individual correlations showed strong relationships at all locations (r^2>0.80). During the RUN, w_{local} increased and tended to plateau at values >0.60, during which thermal discomfort continued to increase. Therefore an exponential relationship existed between the two variables and when w_{local} reaches a ceiling level another factor must be driving discomfort higher. Lee et al. (2011) claimed the reliability of predicting comfort was reduced at higher *w*, which is supported by the findings of this study. However, whether it is the measurement of *w* that is unable to predict thermal comfort when sweat production is high or whether thermal comfort is not driven by the production of sweat at higher sweat rates requires attention. Firstly, at high metabolic rates T_c will continually increase unless the thermal balance is maintained by heat lost from the body. Evaporation of sweat is the main avenue for heat loss in conditions such as those employed during the RUN. T_c increased and was significantly higher at the end of the RUN compared to the WALK. As the strength of the relationship (r^2) between whole body thermal comfort and w_{body} reduces from the WALK to RUN the opposite occurs for thermal comfort and T_c. These results suggest that there may be a limit for when w_{body} influences thermal comfort prior to a continually increasing T_c. Secondly, w was measured in the present study used humidity sensors located in the microclimate, approximately 0.2 cm from the skin. Even though it is relatively small, the distance between the humidity sensor and the skin may not be sufficient to provide a true representation of w_{local}. If the skin is fully saturated with sweat then it should have reached a maximum value of 1.0, yet in some cases the skin appeared to be completely saturated, but w_{local} did not exceed 0.85 ± 0.09. According to Berglund and Cunningham (1986) w based on rationale indices tend to underestimate actual w and values should be used with caution. It is plausible that a measurement artefact may cause the underestimation of w_{local}, but the ceiling effect observed in w_{local} may be a true representation or the values illustrate the issues associated with the measurement of w_{local}. In such cases this suggests that the measured w_{local} is unable to predict thermal comfort and, as a result, an additional predictor (ΔGSC) was chosen assuming that this would not suffer from a ceiling effect at high sweating levels.

A strong relationship exists between local thermal comfort and ΔGSC, which is strengthened from the WALK ($r^2>0.80$) to the RUN ($r^2>0.93$). When sweat production increases as seen during the RUN, ΔGSC has a stronger relationship with thermal comfort than w_{local}. Notably, w_{local} still demonstrated strong relationships with thermal comfort as it indicates the amount of moisture present on the skin surface, yet our receptors that sense temperature and influence thermal comfort are located in the epidermis; this may explain why stronger relationships were found between thermal comfort and ΔGSC than w_{local}. ΔGSC provides information not only about what is happening on the skin surface but also within the epidermis where the receptors are located and this may be the reason that it improves its relationship with perceptual responses. These findings suggest it is not the function of sweating that cannot predict thermal comfort during high sweat rates but w_{local} as a parameter on its own.

The classic work of Gagge et al. (1967) demonstrated the diminishing role of T_{sk} on thermal sensation as it rises above 33°C. It is proposed that sweating maintains T_{sk} at a favourable level and thus thermal sensation does not increase but discomfort will. This continual increase in thermal discomfort was found to correlate with w. In the present study, T_{sk} demonstrated moderate-strong relationship with thermal comfort, which actually improved from the WALK to the RUN despite a significantly higher GSL. Although this does not support the findings of Gagge et al. (1967), the equations in Table 7.5 and Table 7.6 indicate that w_{local} and ΔGSC will predict thermal comfort better than T_{sk}.

Multiple regression analysis was used to predict local thermal comfort using the combined data from both conditions; the equations are displayed in Table 7.5 and Table 7.6. The strength and significance of these models support their ability to predict thermal comfort. However, the validity of the comfort predictions for new data, including different ambient conditions, exercise intensities and/or clothing has yet to be confirmed. For now, these predictions are limited to the realms of this study. According to Table 7.5 and Table 7.6 there is a mixture of parameters that can be used to predict thermal comfort across different parts of the body. Practically, however it does not make sense to measure different parameters across the body based on these results (i.e. w_{local} on the chest but w_{local} and T_{sk} at the abdomen). It is more feasible to suggest that during conditions where sweat production and/or thermal discomfort are low then one parameter should be used across all locations. Furthermore, thermal comfort had strong relationships with both w_{local} and ΔGSC during both conditions. Therefore during conditions of low sweat production or when thermal discomfort is minimal both ΔGSC and w_{local} can be used as a predictor of thermal comfort. However, if sweat production is high and thermal discomfort expected to be greater than 'slightly uncomfortable' then ΔGSC should be used as a predictor. Table 7.5 and Table 7.6 is the combined data of the WALK and RUN and overall, w_{local} had the strongest relationship with thermal comfort. However, during high sweat production w_{local} will reach ceiling values and the sensitivity of w_{local} to predict thermal comfort beyond an uncomfortable state diminishes and the uncertainty will increase dramatically in the exponential part of the curve. Therefore it is proposed that w_{local} can only be used in low heat strain conditions, whilst ΔGSC could be used in both conditions.

7.4.2 Regional differences in sensitivity to sweat

The thermal comfort limit was defined as the point at which the participants no longer felt comfortable. These were determined for w_{local} and are displayed in Figure 7.4 According to w_{body}, the whole body thermal comfort limit occurred at 0.30 during the WALK and 0.42 during the RUN. Although the present data is outside the validity of the equations proposed by Nishi and Gagge (1977) for the comfort limits in exercise, they claimed that comfort limit is relative to metabolic rate which is supported by the higher w_{body} value required during the RUN. During the WALK, local thermal comfort limits suggest that the upper arms and upper legs are the most sensitive areas, due to the lower w_{local} required to no longer feel comfortable. The areas of the torso were the least sensitive. The comfort limits during the RUN generally occurred at higher values than the WALK. The findings coincide with Fukazawa and Havenith (2009) and

Umbach (1982) who found the extremities to be more sensitive than the torso regions. A comparison with the findings in Chapter 5 will be discussed later.

As ∆GSC has not been previously used to predict thermal comfort no comparisons can be made to the literature. The comfort limits for the chest, upper back, upper arm and upper leg occurred at the following respective values: 1.9µS, 1.6µS, 1.6µS and 2.6µS. The values were similar during the RUN. These values are very small in comparison to the range of ∆GSC achieved and the observed small differences between the comfort limits maybe questioned for their practical significance. What may be more informative to know is the degree of discomfort experienced as this may indicate areas that drive discomfort to higher levels. This is particular true for the upper and lower legs as according to their w_{local} comfort limits, they are very sensitive areas due to lower comfort limits, yet they score the lowest discomfort scores at the end of the RUN (-3.1 and -2.9, respectively). According to Figure 7.3, the relationship between thermal comfort and ∆GSC and the slope of the lines suggests that discomfort is relative to the amount of sweat produced for that specific body region. The upper and lower legs may have scored the lowest final comfort votes, but they also had the lowest w_{local} (and ∆GSC) at the end of exercise. This raises questions to whether the legs can be described as the most sensitive area. According to Figure 7.4 the regional differences in the thermal comfort limit (as indicated by w_{local}) occur. This is prominent at the upper leg and lower back, which both had a discomfort score of approximately -3.0, but a w_{local} of 0.50 and 0.76, respectively. Although w_{local} and ∆GSC measure a similar concept (sweat), albeit from slightly different perspectives they provide different findings. As stated earlier, past researchers have used w to predict thermal comfort limits and therefore restricted the methodology to low w_{local} and discomfort scores. To the author's knowledge this is the first experiment to compare thermal comfort over different exercise intensities and the results suggest that higher discomfort scores are relative to the amount of sweat produced. This supports findings from Lee et al. (2011) who noted that the areas perceived as the wettest regions were the upper back, chest, front and back neck and forehead while the palms, feet and dorsal hands were the least wet regions. These areas, according to Smith and Havenith (2011, 2012) are areas of high and low sweat production respectively. In this light, it may be more relevant to considered thermal comfort in two forms, its onset and the degree of discomfort experienced.

7.4.3 w_{local}, ∆GSC and wetness sensation during different exercise intensities

Hygroreceptors have been reported to exist in animals, but none have been found in humans. As such, research has attempted to find correlations of a variety of other physiological responses with the perception of wetness and/or sweating (Bentley, 1990; Plante et al. 1995; Hollies et al., 1979). The mechanism of evaporative heat loss has frequently been identified as a cause of wetness sensation due to the cooling of local T_{sk} (Bentley, 1990). Bentley (1990) reported that cold temperature induced by a tight fitting garment (of even pressure) stimulated the feeling of wetness in the absence of moisture. This has also been supported by Plante et al. (1995) who noted that participants sensed the skin as being 'damper' with larger drops in T_{sk}. Recent research by Newton et al. (2009) found that the initial perception of microclimate RH change, (but no change in sweat production), is linked to the rate of change of local T_{sk}. However, exposure to hot conditions or with exercise causes an increase in T_{sk}, sweat rate and the sensation of wetness. In the present experiment, T_{sk} increased significantly from rest to exercise and the sensation of wetness was still apparent. Therefore the wetness sensation reported in the present study cannot be attributed to a drop in T_{sk}, contrary to suggestions by others (Bentley, 1990; Plante et al. 1995; Newton et al. 2009). Additionally, there was no clear pattern between areas reporting high wetness sensation and areas displaying the largest increase in T_{sk}. Bentley (1990), Plante et al. (1995) and Newton (2009) investigated the perception of wetness via changing the microclimate around the participants or applying fluid onto the skin surface. The present study investigated the perception of wetness through the process of sweat production and sweat travelling through the skin to the surface. In addition to this, T_{sk} increased in this study whereas the listed studies had controlled conditions where a decrease in T_{sk} occurred during inactivity. Different afferent inputs must be apparent in the sensation of wetness when T_{sk} increases and sweat is produced with exposure to heat stress and/or exercise compared to when T_{sk} is stable and decreases as a result of wet stimulation as described by others. The likely result of a wet sensation may be attributed to the presence of sweat which may stimulate several receptors in the skin which is perceived as being wet. When sweat is produced, it is transferred through the epidermis and released onto the skin surface. During this process the epidermis swells and the sensitivity of receptors increases (Kerslake, 1972; Willis, 1985, cited in Li, 2001, p.37). Therefore large differences between our perceptual responses exist when water is either applied onto the skin or changes in the microclimate than when sweat is produced and released. Unfortunately as both local T_{sk} and w_{local} and ∆GSC were allowed to increase simultaneously direct assumptions about what is controlling wetness sensation cannot be implied, but an important conclusion is that a drop in T_{sk} is not required.

During both conditions w_{local} and ΔGSC had stronger relationships with wetness sensation than T_{sk} (see Table 7.7). This supports the claim that wetness sensation is not necessarily influenced by T_{sk}. As with thermal comfort, the ability to detect moisture (as scored on the wetness sensation scale) is relative to the amount of sweat produced. For example, the upper and lower legs had the lowest wetness sensations score at the end, which corresponded with low w_{local} and ΔGSC. Smith and Havenith (2011) identified the extremities as producing substantially less sweat than the torso.

7.4.3 The relationship between perceptual responses

It is clear that a strong relationship exists between thermal comfort and wetness sensation, indicating how closely linked they are in perception. As research has consistently suggested that thermal comfort is influenced by w_{local} in warm conditions, it is unsurprising to observe this finding. Interestingly, at some locations the discomfort associated with a certain wetness level was lower during the RUN compared to the WALK. This may be associated with the ambient conditions which were higher during the WALK. A similar curve between thermal comfort and wetness sensation existed for all locations and in comparison to the relationships between thermal comfort and w_{local}, or ΔGSC there were no variations between locations. Therefore, although there may be differences between the amount of moisture that causes discomfort or the sensation of wetness across regions, once a given wetness sensation is reached the thermal comfort will be the same regardless of location.

7.4.4 Comparison with Chapter 5

Originally w_{body} of 0.25-0.3 has been prescribed as the whole body thermal comfort limit (Gagge et al., 1969a), which was later suggested to be related to metabolic rate (Nishi and Gagge 1977). The hypothesis that we accept more sweat (w) on the skin with increasing metabolic rate is supported with the findings of this study, as the whole body thermal comfort limit is 0.30 and 0.42 for the WALK and RUN respectively. Higher local thermal comfort limits were found in Chapter 5, suggesting more sweat was required locally to influence thermal comfort when w_{local} is not distributed naturally. This seems plausible as physiological responses such as w_{local}, local T_{sk} and T_c were kept low and stable in Chapter 5. In the present study, all physiological responses increased simultaneously and any changes in local thermal comfort can be attributed to other local or whole body changes.

The match of the graphs (Figure 7.8) of the different studies for torso w_{local} and w_{body} suggest that sensations there are not influenced by the distribution of w over the body and that the torso is not much influenced by other areas. However, at the extremities, the data points from Chapter 5 shift to the right, suggesting these areas are less sensitive than concluded from this chapter. The fact that discomfort levels do not increase from the values observed in this chapter until w_{local} is artificially raised above other zones suggests that in the present study the discomfort in these areas is governed by other (wetter) body parts. When w_{local} varies naturally, as in the present study, the torso areas will naturally produce more sweat than the extremities (Smith and Havenith, 2011 and 2012). It is possible that these areas will produce so much more sweat than the extremities that they dominate local thermal comfort across the whole body. It seems likely that he findings in Chapter 5 indicate the true local comfort limits for each respective zone while the present study provides a global picture of how local regions interact and influence local thermal comfort across the body. Nakamura et al. (2008) speculated that regional differences in thermal comfort are a result of the central nervous system weighing the input from each area. As the torso contains vital organs it is essential to protect these from overheating. Therefore, in the interest of protecting against thermal strain, when w_{local} increases across the torso it has a strong influence on the thermal comfort of many body regions due to a shift in attention to areas of the body that produce more sweat. The suggested influence of the torso on the sensitivity values observed for the extremities explains why regional sensitivity was not consistent between Chapter 5 and the present study. This also illustrates why it was important to replicate the work of Fukazawa and Havenith (2009), who claimed the extremities to be more sensitive than the torso but failed to keep torso w_{local} significantly below that of the extremities. This problem was addressed in Chapter 5, in which alterations were made to Fukazawa and Havenith's methodology to create a clear contrast between zones, with the goal to determine whether the extremities were actually more sensitive than the torso. In Chapter 5, w_{local} across the torso was indeed better controlled when the extremities were manipulated and the arms were not the most sensitive areas. As the torso has demonstrated to have a strong influence on the thermal comfort limits of many body sites in the present study, suggests that their findings may have under-predicted the true local thermal discomfort threshold of the extremities. The seemingly conflicting results of the present study, Fukazawa and Havenith's and chapter 5 can thus be explained with the above discussed model of segmental interaction.

7.5 Conclusions

The natural variation of physiological responses (ΔGSC, w_{local} and T_{sk}) and perceptual responses were measured in male participants and their relationships analysed. The following conclusions were made.

- At high levels of sweat production w plateaued around 0.60-0.80 indicating a ceiling effect.
- Local skin wettedness never exceeded 0.85 ± 0.09 despite areas appearing completely saturated with sweat. It is plausible that a measurement artefact caused an underestimation of w_{local} but the ceiling effect observed in w_{local} may be a true representation.
- A strong linear relationship exists between local thermal comfort and w_{local} during the WALK ($r^2>0.78$). However, the ceiling effect observed during the RUN resulted in an exponential relationship between thermal comfort and w_{local} which reduced its ability to predict thermal comfort ($r^2>0.75$) for higher sweat rates.
- Strong linear relationships exists between local thermal comfort and ΔGSC, which is strengthened from the WALK ($r^2>0.80$) to the RUN ($r^2>0.93$). When sweat production increases as seen during the RUN, ΔGSC has a stronger relationship with thermal comfort than w_{local} and does not show a ceiling effect.
- It is proposed that w_{local} should only be used to predict thermal comfort in conditions of low sweat production, whilst ΔGSC can be used in conditions of both low and high sweat production.
- According to w_{local}, there are regional differences in local thermal comfort limits, with the extremities being more sensitive than the torso. However, thermal comfort may be relative to the amount of sweat produced as the torso areas scored the highest discomfort scores, which were mirrored by the highest w_{local} and ΔGSC.
- According to ΔGSC, there are no regional differences in local thermal comfort limits; instead thermal comfort is relative to the amount of sweat produced for that specific body region.
- A drop in skin temperature is not required to stimulate a wetness sensation.
- There is a very strong link between thermal comfort and wetness sensation.

- The discomfort associated with a certain wetness level is lower in higher intensity exercise.
- Although there may be differences between the amount of sweat that causes discomfort (or the sensation of wetness) across regions, once a given wetness sensation is reached the thermal comfort will be the same regardless of location.
- A model of segmental interaction is proposed; when w_{local} varies naturally, the torso area will naturally produce more sweat than the extremities. The thermal comfort in areas of naturally low w_{local}, such as the extremities, appears to be dominated by the torso areas.

Chapter eight – Laboratory study 5

A comparison of skin wettedness and galvanic skin conductance as predictor of thermal comfort and wetness sensation during different exercise intensities in females

8 Chapter Summary

This chapter aims to determine whether local skin wettedness (w_{local}) or galvanic skin conductance (GSC) should be used as physiological indicator of females' thermal comfort during different exercise intensities. In the previous chapter w_{local} reached ceiling values during high metabolic rates whilst discomfort continued to increase. On the other hand GSC continually increased throughout the trial and proved to be a better predictor of thermal comfort than w_{local} during high sweat production. These findings were limited to males as females are known to produce less sweat than males. To extend this to females, in a balanced order, ten female participants took part in two conditions that aimed to stimulate different physiological and perceptual responses. Participants exercised at ~20% $\dot{V}O_{2max}$ for 45 minutes (WALK) (28.7 ± 3.2°C, 32.3 ± 3.9 % RH). On a separate day they exercised at ~70% $\dot{V}O_{2max}$ for 45 minutes (RUN) (25.9 ± 2.1°C, 32.3 ± 3.8% RH). During both tests w_{local}, change from baseline in GSC (ΔGSC), T_{sk}, thermal comfort and wetness sensation were recorded. The relationship between the perceptual responses and the physiological response when sweat production was low and high was investigated. The thermal comfort limit was defined as the w_{local} that corresponded to a comfort vote of -1 when participants no longer felt comfortable (i.e. the transition away from comfort). The results suggest that both w_{local} and ΔGSC are moderate to strong predictors of thermal comfort ($r^2>0.52$ and $r^2>0.90$, respectively) and wetness sensation ($r^2>0.58$ and $r^2>0.89$, respectively). In comparison to males, w_{local} did not reach ceiling values which is likely due to the lower sweat production of females. The females have a similar pattern to males' regional sensitivity which suggests the extremities are more sensitive than the torso. However, this is associated with the model of segmental interaction; the areas of the torso naturally produce much more sweat than the extremities that they dominate local thermal comfort across the whole body. Females had lower thermal comfort limits than males at all locations; indicating a higher sensitivity to the initial presence of sweat. Interestingly, female thermal comfort limits occurred at a lower w_{local} during the RUN in

comparison to the WALK, which is opposite of the males' data and opposes findings in the literature. This too suggests that females are more sensitive to the initial presence of sweat, which may be exercise intensity dependent. Females experienced less discomfort and wetness sensation than males at the end of exercise which coincides with lower gross sweat loss, w_{local} and ΔGSC than males.

8.1 Introduction

Many physiological differences between genders, such as body fat percentage, surface area, hormones and cardiovascular fitness explain the gender differences reported in thermoregulatory function (McLellan, 1998; Fox et al. 1969). However, when matched for $\dot{V}O_{2\text{max},}$ body fat percentage and/or surface area to mass ratio, researchers have eliminated gender differences to heat stress (Moran et al. 1999; Havenith and van Middendorp, 1990; Frye & Kamon, 1981; Avellini & Kamon, 1980). In Chapter 4, males and females of a similar fitness level were compared for their transient and steady state sensitivity to a warm stimulus during rest and exercise. Overall, the data suggests that females are more sensitive to a hot stimulus, which was more prominent during steady state responses. These findings support an overall consensus that females are more sensitive than males to thermal stimuli (Golja et al. 2003), thermal pain (Fillingim et al. 1998; Lautenbacher and Strain, 1991) and pain (Otto & Dougher, 1985). Gender differences in sensitivity to sweat have received comparably little interest despite research confirming lower sweat rates in females (Smith and Havenith, 2012; Inuoe et al., 2005; Havenith et al. 2008; Fox et al. 1969; Bittell & Henane, 1975). According to Inuoe et al. (2005) females rely more on convective heat loss than evaporative heat loss when exercising in warm conditions due to a lower sweat production. The increased sensitivity to temperature may be a compensatory mechanism for a lower sweat production in order to encourage behavioural responses to avoid excessive heat storage. However, further research needs to address this.

In a controlled experiment, local thermal comfort limits to w_{local} were identified for males and regional differences were evident (Chapter 5). The findings suggested that arms were the least sensitive area whilst the legs and areas of the torso were the most sensitive. In a subsequent trial (Chapter 7) these comfort limits were checked in uncontrolled conditions where w_{local} and perceptual responses varied naturally. The findings suggested that the regional differences in the thermal comfort limits to w_{local} are not the same. When w_{local} varies naturally the torso areas will produce more sweat than the extremities (Smith and Havenith, 2011, 2012) and these areas may produce so much more sweat than the extremities that they dominate local thermal comfort across the whole body.

These findings were both carried out on male participants and whilst it may be useful to indentify the local thermal comfort limits to w_{local} on females using the same methodology as Chapter 5, the findings from Chapter 7 are more informative for a sports clothing designer as they are more ecologically valid. Fukazawa and Havenith (2009), Umbach (1982) and chapters of this thesis have investigated regional differences in perceptions of thermal comfort to w_{local} on male participants only. To date, no authors have identified the relationship between thermal comfort and w_{local} in females. The findings suggest that w_{local} is a strong predictor of local thermal comfort during situations of low sweat production. On the other hand, ∆GSC was found to be a stronger predictor during high sweat production. As females have a lower sweat production than males (Smith and Havenith, 2012; Havenith et al. 2008), it would be of interest to determine which parameter ($w_{\mathrm{local},}$ ∆GSC or T_{sk}) can predict thermal comfort best.

8.1.2 Aims

The present study aimed to determine the relationship between thermal comfort and w_{local} and ∆GSC in female participants. These results will be compared to Chapter 7 to determine whether any similarities exist between male and female sensitivity to sweat. To further the research carried out in previous chapters, the link between wetness sensation and w_{local} and ∆GSC will also be explored.

8.2 Methods

The experimental methodology is outlined in Chapter 3; however the pre-test session measuring anthropometrics (skin fold analysis) was not carried out. A summary with specific details to this experiment will be described here.

8.2.1 Participants

Ten Caucasian females (height 163.9 ± 5 cm, mass 59.1 ± 6.3 kg, age 22 ± 5 yrs, $\dot{V}O_{2\mathrm{max}}$ 50.7 ± 7.7 ml·kg·min^{-1}) were recruited from the staff and student population at Loughborough University.

8.2.2 Methodology

The methodology is identical to that for the males in Chapter 7, to which the data will be compared. In summary, participants completed a submaximal fitness test to estimate maximum aerobic capacity ($\dot{V}O_{2max}$). On separate days they completed two main trials in a balanced order. Upon arrival at the laboratory, participants self inserted a rectal thermometer. Eight humidity sensors and eight skin thermistors were attached to the chest, abdomen, upper back, lower back, upper arm, lower arm, upper leg and lower leg to measure w_{local} and T_{sk} (respectively). Four electrodes were attached to the chest, upper back, upper arm and upper leg to measure ∆GSC. Participants wore 100% polyester long sleeve top and trouser ensemble as described in Chapter 7. Once dressed and fully equipped, participants sat in a thermoneutral environment (21.5 ± 0.8°C, 32.6 ± 6.1 % RH) for 15 minutes to allow physiological responses to stabilise. Following the rest period, participants entered the environmental chamber where they began exercising for 45 minutes. During the WALK, participants exercised for 45 minutes at 4.5 $km \cdot hr^{-1}$ in a chamber at 28.7 ± 3.2°C, 32.3 ± 3.9 % RH, with no wind. During the RUN, participants walked at 4.5 $km \cdot hr^{-1}$ for 5 minutes, followed immediately by a run at 70% $\dot{V}O_{2max}$ for 40 minutes in a chamber at 25.9 ± 2.1°C, 32.3 ± 3.8% RH, with no wind. The experiment was treated as a repeated measures design.

During the trial local and whole body thermal comfort and wetness sensation were rated every 5 minutes (see Chapter 7, Table 7.2). Local T_{sk}, w_{local}, ∆GSC and T_c were continuously measured and averaged for every 5 minutes. The thresholds for when the skin no longer feels comfortable or dry will be defined as the w_{local} that corresponds with a comfort vote of -1 and a wetness vote of 1. These values will be used to define the sensitivity of localised zones to w_{local} and w_{body}. This method is the same as that used in previous chapters and by Fukazawa and Havenith (2009) and Umbach (1982).

8.2.3 Clothing

Participants' wore a 100% polyester long sleeve top and trouser ensemble with a high permeability for heat and vapour transfer (thermal resistance of 0.154 $m^2 \cdot K \cdot W^{-1}$ and water vapour resistance of 35.9 $m^{2} \cdot Pa \cdot W^{-1}$) tested on a thermal manikin (Newton, Measurement Technology Northwest, USA). The clothing was loose fitting across the body. Participants wore their own socks and athletic trainers.

8.2.3 Data analysis

Statistical analysis was conducted using Statistical Package (SPSS) version 18.0. The main effect of condition, location and time was analysed using three-way repeated measures ANOVA. Post hoc comparisons using Bonferroni correction were performed to assess individual differences. In some instances, differences between conditions were analysed using paired samples t-test and corrected for multiple comparisons.

Correlation analysis was performed to assess the relationship between perceptual and physiological responses. Multiple regression analysis was used to determine the best predictors of perceptual responses for the two conditions. Unless otherwise stated, all measurements are presented as means with standard deviations (± S.D) and the significance is defined as $p<0.05$.

8.3 Results

8.3.1 Experimental design

No significant differences were found in T_c at rest between the WALK (37.32 ± 0.4°C) and RUN (37.4 ± 0.6°C) ($p>0.05$). However, the increase in T_c from baseline to the end of the experiment was significantly less for the WALK (37.7 ± 0.9°C) than the RUN (38.4 ± 0.5, $p<0.001$). GSL was higher, but not significant, during the RUN compared to the WALK (335.5 ± 90.8 and 260.9 ± 85.1g·m^{-2}·hr^{-1}, respectively).

Figure 8.1a-c shows the mean values at the end of each condition (WALK and RUN) for w_{local}, T_{sk} and ΔGSC. All physiological and perceptual responses were higher during the RUN compared to the WALK. The main effect of condition, location and time was analysed using three-way repeated measures ANOVA. The results revealed a significant effect of condition on ΔGSC ($p<0.05$) but not on local T_{sk} or w_{local}. A significant effect of time was found on all parameters as they increased from rest to the end of exercise. No significant effect of location was observed for ΔGSC. However, a significant effect of location ($p<0.001$) was observed for local T_{sk} and w_{local} and the results from the pairwise comparison (with and without Bonferroni corrections) can be viewed in Table 8.1. Overall, the back had a higher local T_{sk}, and w_{local} than other areas and the extremities were lower than areas of the torso.

***Main findings*:**

- all physiological responses, discomfort and wetness sensation were higher at the end of the RUN compared to the WALK;
- overall, areas of the torso had higher w_{local} and T_{sk} than the extremities.

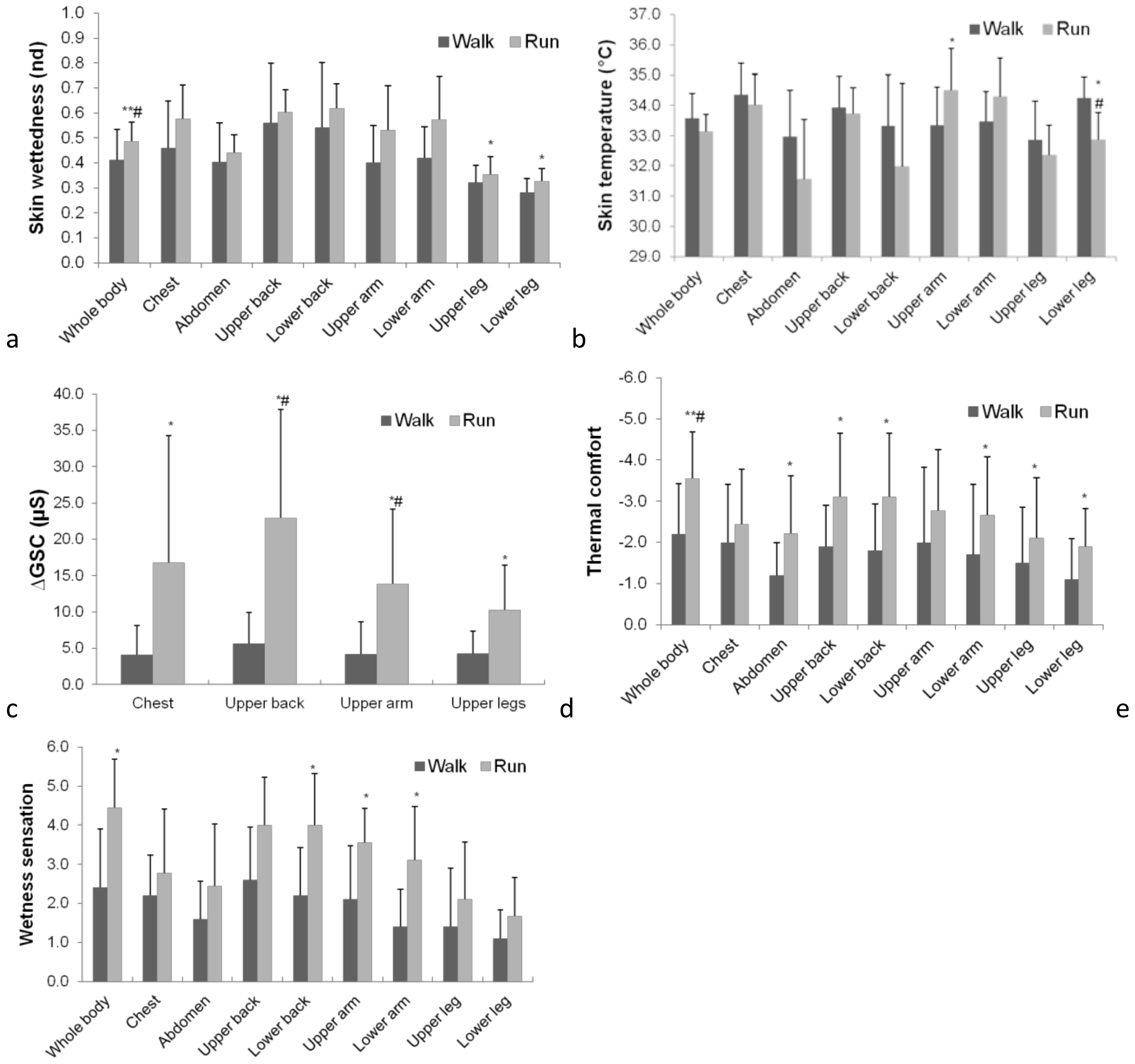


Figure 8.1: The mean values (±SD) of a) local skin wettedness, b) local skin temperature, c) ΔGSC, d) thermal comfort and e) wetness sensation measured at the end of the WALK and RUN. Significant differences between WALK and RUN during rest is denoted by * ($p<0.05$) and ** ($p<0.001$) (without corrections) and by # $p<0.05$ (with Bonferroni adjustment).

8.3.4 The relationship between thermal comfort and physiological variables

Figure 8.2 and Figure 8.3 illustrate the relationships between local thermal comfort and ΔGSC and w_{local} (respectively) during the WALK and the RUN. The strength of the relationship (r^2) between each variable and thermal comfort is displayed in Table 8.2. Unlike the male data (in Chapter 7), the relationship between thermal comfort and w_{local} is linear during both conditions as no ceiling effect was observed with w_{local}. These relationships are moderate to strong in both conditions ($r^2>0.52$), but generally improve during the RUN ($r^2>0.73$). Thermal comfort had a curvilinear relationship with ΔGSC and the results revealed strong non-linear relationships ($r^2>0.89$); which was generally stronger than w_{local}. Local T_{sk} did not consistently have good relationships with local thermal comfort; as a result the graphs are not displayed.

Table 8.1: Significance of pairwise comparison between locations for w_{local} ($$ $p<0.05$, with Bonferroni corrections ($ $p<0.05$, without corrections), for T_{sk} (* $p<0.05$ with Bonferroni corrections (** $p<0.05$ without corrections). No significant differences were observed for ΔGSC.

	Whole body	Chest	Abdomen	Upper back	Lower back	Upper arms	Lower arms	Upper legs	Lower legs
Chest	$*								
Abdomen		*							
U back	$*	$*	$*						
L back	$	*	$	*					
U arms		$*		$*	$				
L arms		*		*	$				
U legs	$	$*		$*	$	$	$		
L legs	$	$	$	$	$	$*	$*	*	

Table 8.2: Individual relationship (r^2) between thermal comfort and ΔGSC, w_{local}, T_{sk}, and T_c . † Indicates non-linear correlation – indicates where analysis was not carried out.

		ΔGSC	w_{local}	Local T_{sk}	T_c
Whole body	Walk	-	0.91	0.90	0.56
	RUN	-	0.94	0.94	0.89
Chest	Walk	0.94†	0.94	0.03	-
	RUN	0.98†	0.92	0.00	-
Abdomen	Walk	-	0.80	0.20	-
	RUN	-	0.73	0.41	-
Upper back	Walk	0.93†	0.95	0.66	-
	RUN	0.96	0.89	0.60	-
Lower back	Walk	-	0.88	0.80	-
	RUN	-	0.92	0.28	-
Upper arm	Walk	0.95†	0.93	0.84	-
	RUN	0.97†	0.94	0.91	-
Lower arm	Walk	-	0.88	0.85	-
	RUN	-	0.89	0.90	-
Upper leg	Walk	0.90†	0.74	0.83	-
	RUN	0.96†	0.89	0.90	-
Lower leg	Walk	-	0.52	0.86	-
	RUN	-	0.86	0.86	-

Stepwise multiple regression analysis was performed in order to predict local and whole body thermal comfort. As with the previous chapter, w_{local} data points from the two conditions appear to overlap. Therefore multiple regression analysis was performed on the combined data of both conditions (Table 8.4). However, for ΔGSC, the data points at the start of both conditions are the same, but there appears to be a transition period at higher levels of GSC (during the RUN), after which the data points shift towards the right, particularly at the torso. Therefore multiple regression analysis was performed to predict local thermal comfort during the WALK and RUN separately, using ΔGSC as a predictor (Table 8.3). Local and whole body thermal comfort can be determined using the regression equations indicated in Table 8.3 and Table 8.4. The high, significant correlations observed from the data analysis revealed these equations are valid for conditions employed by this experiment.

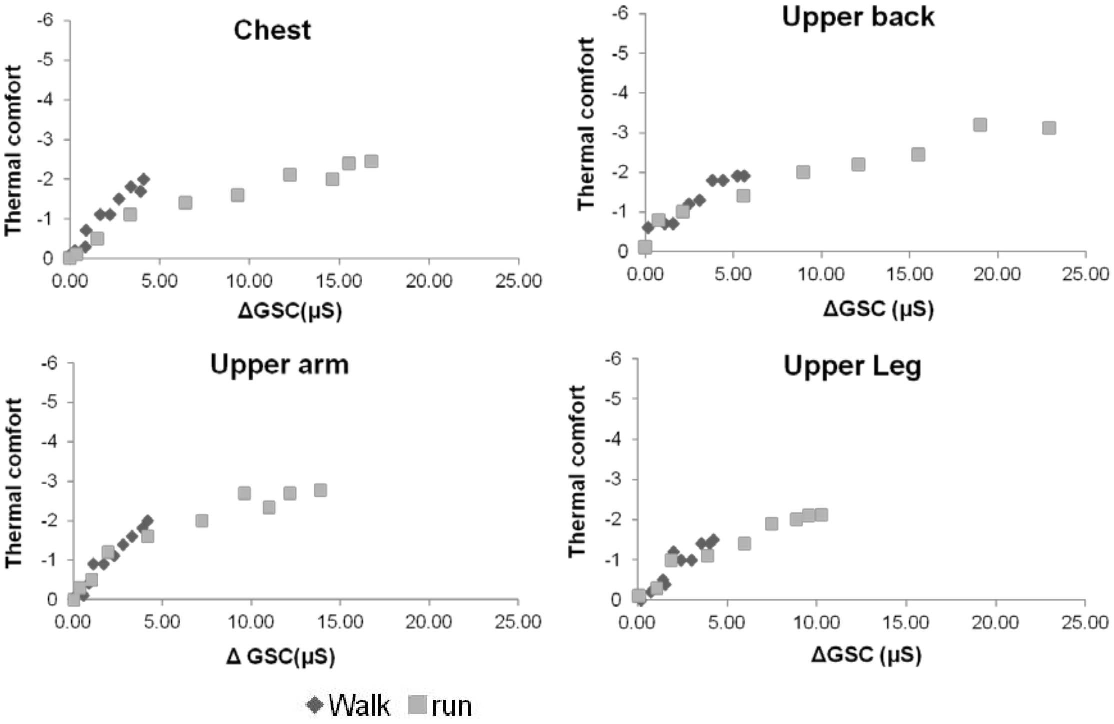


Figure 8.2: The relationship between local thermal comfort and ΔGSC in both conditions (WALK and RUN), at each location.

Main findings:

- unlike the males, no ceiling effect is observed with w_{local} during the RUN. Therefore moderate to strong linear relationships were found between local thermal comfort and w_{local} during both conditions ($r^2>0.52$);

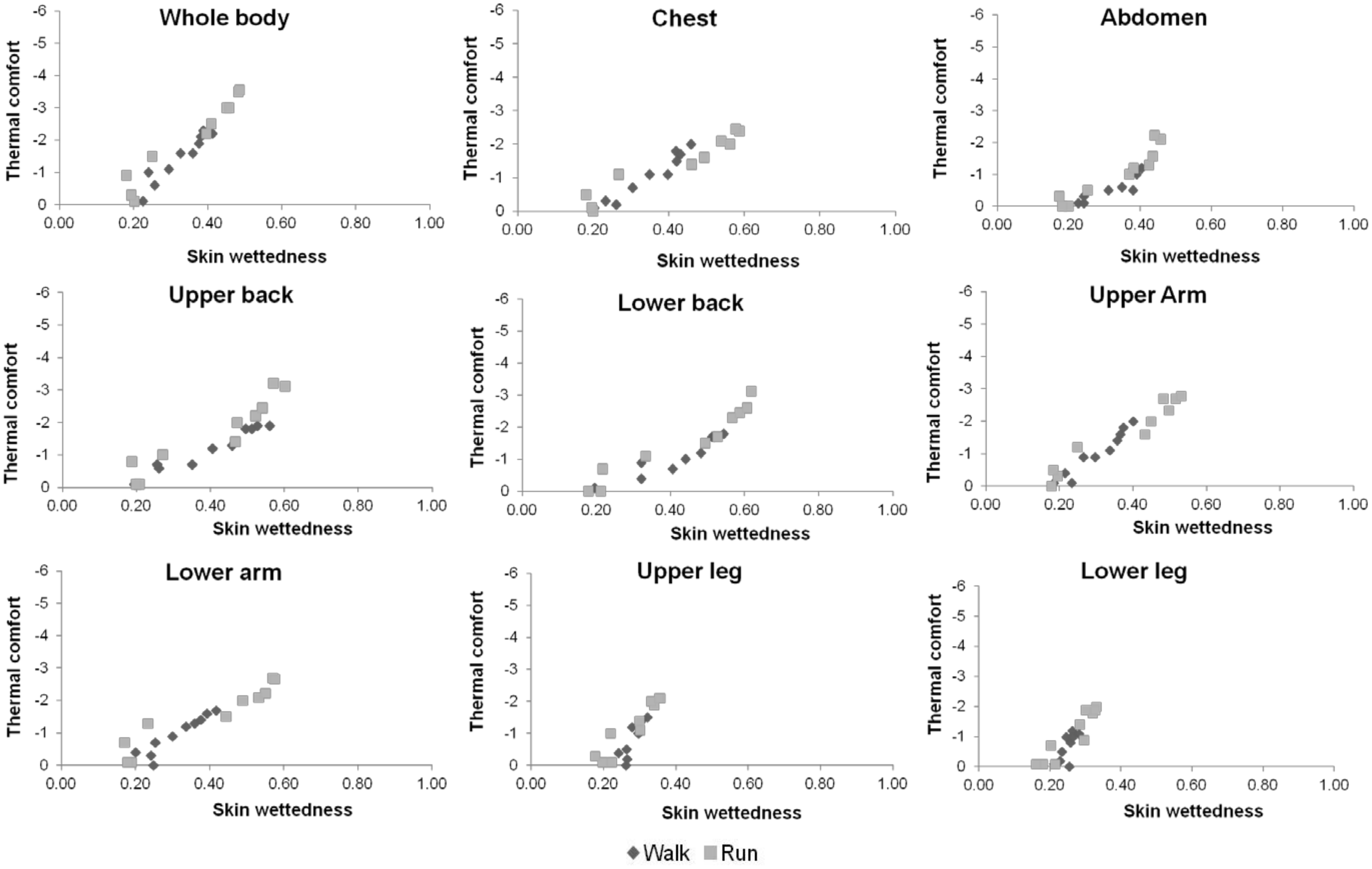


Figure 8.3: The relationship between local thermal comfort and w_{local} in both conditions (WALK and RUN), at each location

Table 8.3: Regression equations for the prediction of female thermal comfort during the WALK and RUN using ΔGSC as a predictor. The regression coefficients (B), their standard error (SE B), the standardised beta value (β) and the strength of the relationship (r^2) between thermal comfort and ΔGSC. (*p<0.05, **p<0.001).

WALK					
Location		B	SE B	β	r^2
Chest	Constant	0.357	0.139		0.94**
	ΔGSC	-1.086	0.097	-0.969	
Upper back	Constant	0.002	0.135		0.93**
	ΔGSC	-0.806	0.081	-0.962	
Upper arm	Constant	0.574	0.140		0.95**
	ΔGSC	0.097	0.097	-0.975	
Upper leg	Constant	0.524	0.178		0.89**
	ΔGSC	-0.967	0.117	-0.946	
RUN					
Location		B	SE B	β	r^2
Chest	Constant	0.249	0.108		0.98**
	ΔGSC	-0.645	0.036	-0.989	
Upper back	Constant	-0.079	0.168		0.96**
	ΔGSC	-0.640	0.051	-0.982	
Upper arm	Constant	0.126	0.150		0.97**
	ΔGSC	-0.808	0.058	-0.983	
Upper leg	Constant	0.246	0.128		0.96**
	ΔGSC	-0.742	0.055	-0.981	

- the strength of the relationship between thermal comfort and w_{local} generally declines from WALK to RUN, whereas it strengthens from WALK to RUN for ΔGSC;
- the relationship between thermal comfort and GSC is initially the same during both conditions. There is a transition at higher level of ΔGSC and the slope between thermal comfort and ΔGSC differs between the two conditions.

8.3.5 Regional differences in thermal comfort perception

The comfort limits are defined as the point at which participants no longer feel comfortable (-1 vote). Local and whole body thermal comfort limits according to w_{local} are displayed in Figure 8.4. A low value indicates an area sensitive to sweat as it takes less sweat on the skin to cause a transition away from comfortable. These areas are depicted with darker colours. According to w_{local}, the values indicate that the arms and legs are the most sensitive during the WALK due to the lower w_{local} values (<0.30), whilst the torso areas are less sensitive as they require higher w_{local} values before participants no longer felt comfortable (>0.30). Overall, lower comfort limits were

Table 8.4: Regression equations for the prediction of female thermal comfort for the whole body and areas of the torso. The shaded boxes illustrate the models which would be the better predictor of thermal comfort. The regression coefficients (B), their standard error (SE B), the standardised beta value (β) and the strength of the relationship (r^2) between thermal comfort and each predictor are shown (*p<0.05, **p<0.001).

Location		B	SE B	β	r^2	Location		B	SE B	β	r^2
Whole body	Constant T_c T_{sk}	93.563 -2.081 -0.525	6.692 0.202 0.098	 -0.727 -0.377	0.934**	**Upper arm**	Constant w_{local}	1.148 -7.322	0.169 0.473	 -0.964	0.930**
	Constant T_c	95.930 -2.599	10.612 0.282	-0.908	0.825**		Constant T_{sk}	16.559 -0.557	2.370 0.074	 -0.872	0.760**
	Constant w_{body}	1.643 -10.036	0.267 0.758	-0.952	0.907**	**Lower arm**	Constant w_{local}	0.756 -5.667	0.186 0.492	 -0.938	0.881**
	Constant T_{sk}	31.167 -1.010	7.346 0.225	 -0.726	0.527**		Constant T_{sk}	24.201 -0.774	2.949 0.090	 -0.897	0.805**
Chest	Constant w_{local}	0.885 -5.552	0.169 0.422	 -0.952	0.906**	**Upper leg**	Constant w_{local}	2.333 -11.762	0.474 1.658	 -0.862	0.743**
Abdomen	Constant w_{local} T_{sk}	-7.033 -6.428 0.259	-7.033 -6.428 0.259	2.952 0.636 0.092	0.862**		Constant T_{sk}	15.850 -0.535	3.383 0.107	 -0.762	0.581**
	Constant w_{local}	1.241 -6.271	0.257 0.745	 -0.893	0.797**	**Lower leg**	Constant w_{local}	2.234 -12.203	0.429 1.650	 -0.867	 0.752**
Upper back	Constant w_{local}	0.931 -5.828	0.253 0.592	 -0.918	0.843**		Constant T_{sk}	9.141 -0.310	3.165 0.098	 -0.599	 0.358*
	Constant T_{sk}	51.927 -1.593	16.086 0.480	 -0.616	0.379*						
Lower back	Constant w_{local} T_{sk}	-10.324 -6.485 0.364	4.488 0.569 0.143	 -1.073 0.240	0.903**						
	Constant w_{local}	1.083 -5.622	0.236 0.522	 -0.930	0.866**						

observed during the RUN, but the pattern across the body remained the same, with the arms and legs being the most sensitive and the torso being less sensitive. As with the previous chapter, identifying the comfort limits according to ∆GSC is pointless due to the small range observed at the comfort limit (1.4 to 2.1 µS) in comparison to the range of ∆GSC data (0.00 to 22.9 µS) over the course of the test. Such small differences at the comfort limit may be meaningless.

The maximum discomfort scored at the end of each trial and the associated w_{local} and ∆GSC are presented in Figure 8.1. As with the previous chapter, maximum discomfort may be relative to the amount of sweat produced (as indirectly indicated by w_{local} and ∆GSC). The chest and upper back had high discomfort votes (>2.0) and the highest w_{local} and ∆GSC, whilst the opposite was true for the lower legs. As with the male data, the only exception appears to be the upper arm during the WALK which has a similar discomfort score to the upper back yet a much lower w_{local} (0.40 ± 0.2 vs. 0.56 ± 0.3).

Main findings:

- local thermal comfort limits (according to w_{local}) indicate that the extremities are more sensitive than the torso areas;
- lower thermal comfort limits for w_{local} are found during the RUN compared to the WALK;
- the degree of discomfort may be relative to the amount of sweat produced, which suggests that the torso will experience stronger discomfort than the extremities;. this coincides with the highest w_{local} and ∆GSC.

8.3.5 The relationship between wetness sensation and physiological variables

The graphs displayed in Figure 8.5 and Figure 8.6 illustrate the relationships between local wetness sensation with ∆GSC and w_{local} (respectively) during the WALK and the RUN. The strength of the relationship (r^2) between each variable and wetness sensation is displayed in Table 8.5. A strong linear relationship between local wetness sensation and w_{local} occurred at all locations ($r^2 \geq 0.58$). The relationships during the RUN were stronger than the WALK for all locations ($r^2 \geq 0.83$). Wetness sensation had curvilinear relationship with ∆ and the results revealed strong non-linear relationships ($r^2 > 0.89$). The strength of these relationships improves from the WALK to the RUN. As with thermal comfort, local T_{sk} did not consistently have good relationships with local wetness sensation and, where relationships did exist, they were linear.

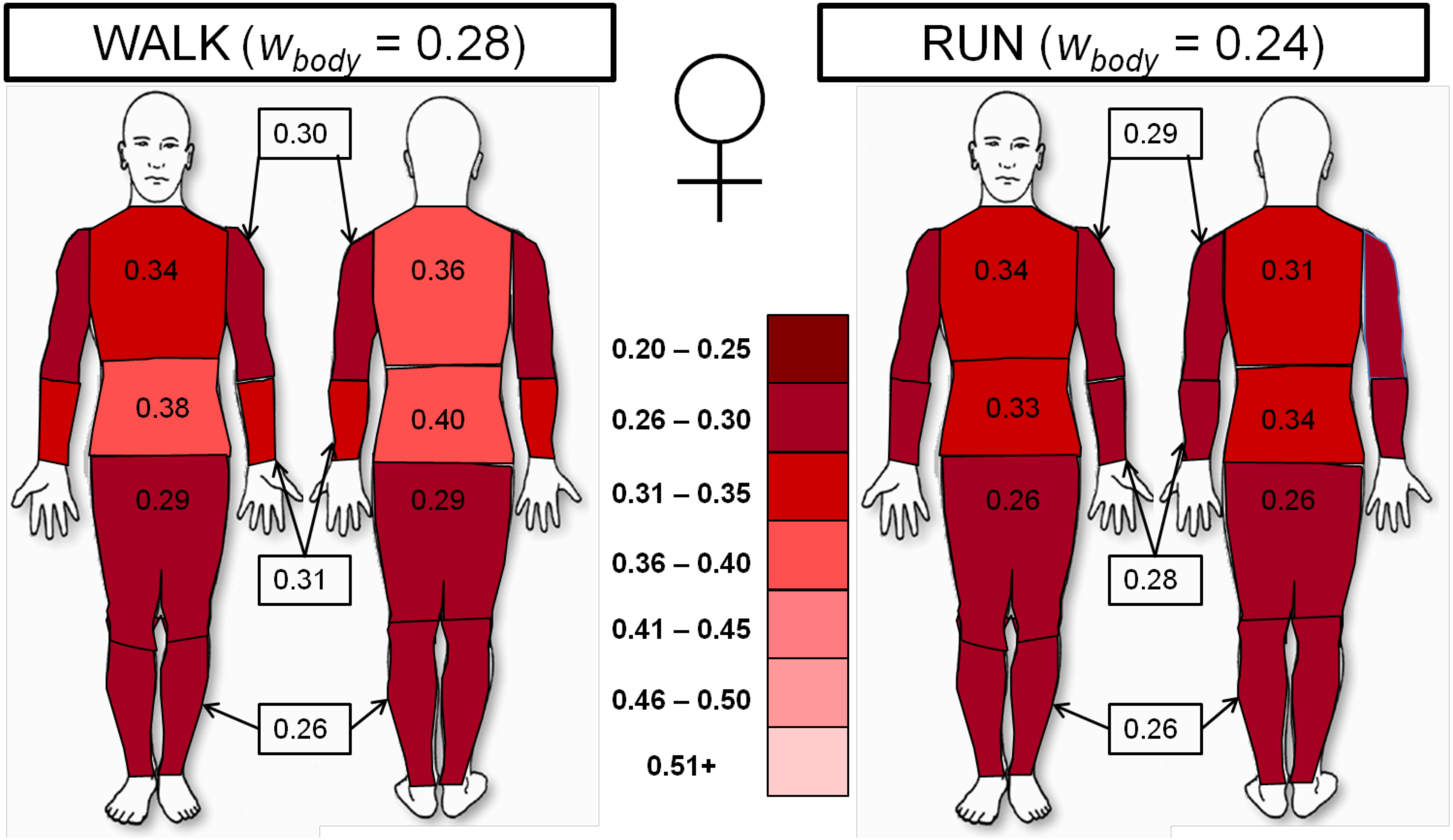


Figure 8.4: The w_{local} thermal comfort limits for each location during WALK and RUN, which corresponds to when locations no longer felt comfortable. Lower numbers indicate higher sensitivity and are depicted with darker colours.

Table 8.5: Individual relationship (r^2) between wetness sensation and ΔGSC, w_{local}, T_{sk}, † Indicates non-linear correlation – indicates where analysis was not carried out.

		ΔGSC	w_{local}	Local T_{sk}
Whole body	Walk	-	0.87	0.90
	RUN	-	0.96	0.94
Chest	Walk	0.90	0.92	0.01
	RUN	0.97	0.94	0.02
Abdomen	Walk	-	0.90	0.47
	RUN	-	0.92	0.19
Upper back	Walk	0.95	0.97	0.67
	RUN	0.96†	0.94	0.61
Lower back	Walk	-	0.90	0.82
	RUN	-	0.94	0.29
Upper arm	Walk	0.96	0.97	0.89
	RUN	0.89†	0.90	0.94
Lower arm	Walk	-	0.88	0.77
	RUN	-	0.91	0.93
Upper leg	Walk	0.91	0.77	0.83
	RUN	0.98	0.88	0.91
Lower leg	Walk	-	0.58	0.79
	RUN	-	0.83	0.86

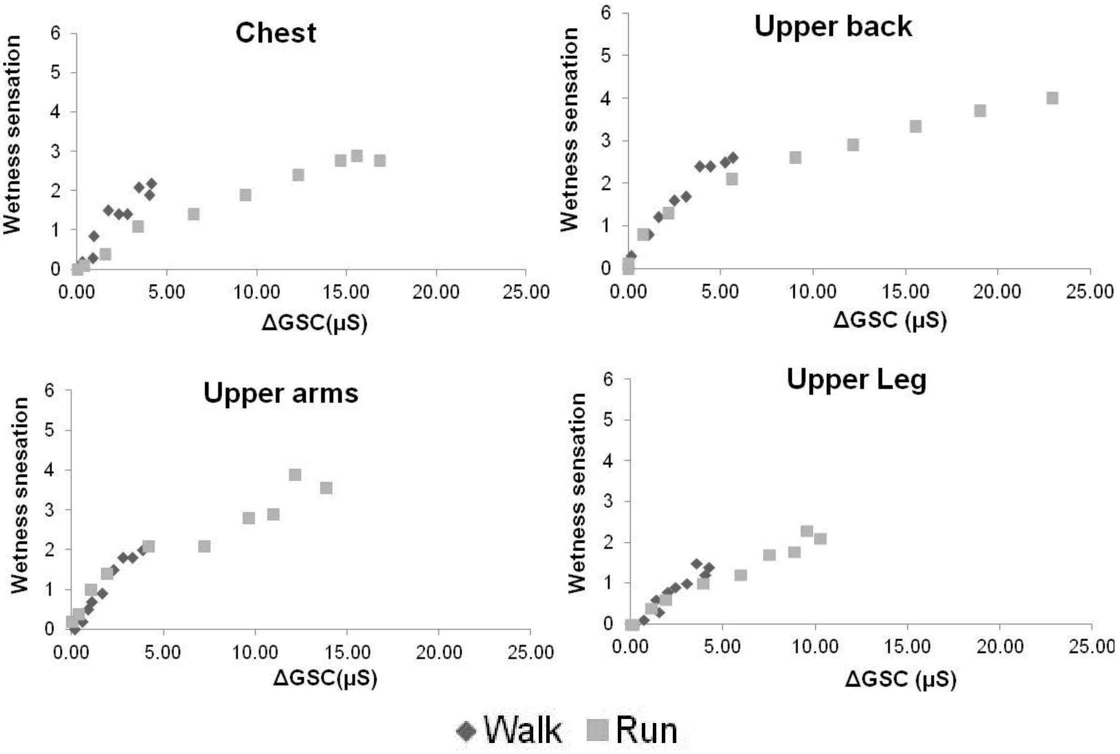


Figure 8.5: The relationship between local wetness sensation and ΔGSC in both conditions (WALK and RUN), at each location.

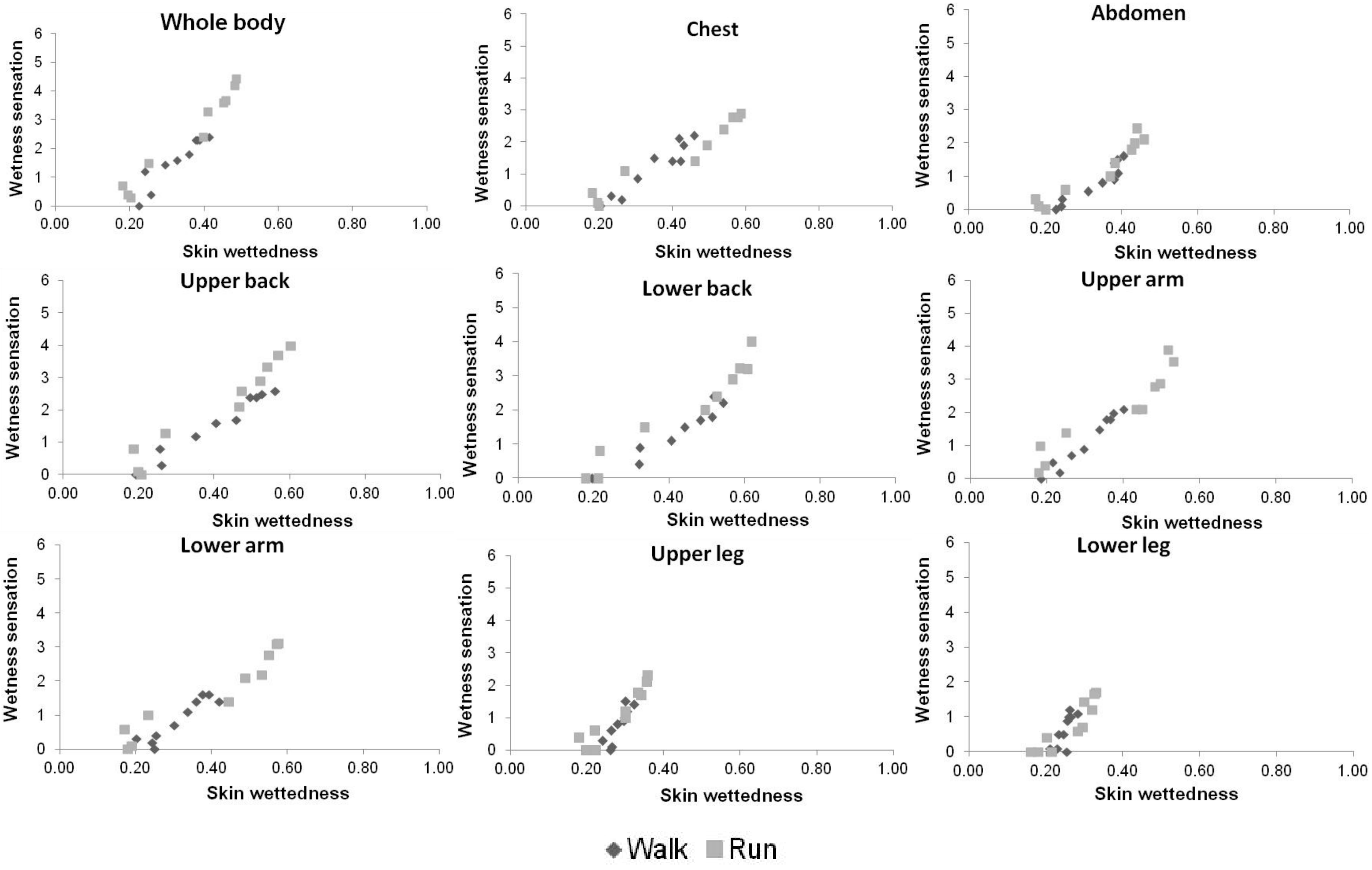


Figure 8.6: The relationship between local wetness sensation and w_{local} in both conditions (WALK and RUN), at each location.

Main findings:

- moderate to strong relationships were found between local wetness sensation and w_{local} and ΔGSC ($r^2>0.58$);
- the strength of the relationship between thermal comfort and w_{local} generally declines from WALK to RUN, whereas it strengthens for ΔGSC.

8.3.6 Gender comparison

Two-way repeated measures ANOVA with gender as a between subject factor was performed on data collected from the end of each condition. The findings revealed a significant effect of gender for w_{local} only, while there were no significant effects of gender for local T_{sk}, ΔGSC or any of the perceptual responses.

Figure 8.7 displays the male and female w_{local} thermal comfort limits during both conditions. Two-way repeated measures ANOVA with gender as a between subject factor was performed on the w_{local} thermal comfort limit. The findings revealed no significant effect of gender, but a significant effect of location. Pairwise comparisons are displayed in Table 8.6 and the results generally indicate that the torso is significantly higher than the extremities.

Table 8.6: Significance of pairwise comparison between locations for the local thermal comfort limits of w_{local} during both conditions (\$ $p<0.05$, with Bonferroni corrections (* $p<0.05$, ** $p<0.001$ without corrections), for the local thermal comfort limits of w_{local} during the RUN only (# $p<0.05$ with Bonferroni corrections († $p<0.05$ without corrections).

	Whole body	Chest	Abdomen	Upper back	Lower back	Upper arms	Lower arms	Upper legs	Lower legs
Chest	*†								
Abdomen	\$\$*†	†							
U back	*†								
L back	\$\$**†								
U arms	†	*†	*	*	*				
L arms		†	†	*	*†	†			
U legs		*†	*	*	\$\$*†	†			
L legs		†	*†	*†	*†	†			

During the WALK, the local comfort limits between genders is similar. Neither male nor female demonstrated an overall higher sensitivity as some locations are more sensitive for males whilst others are more sensitive for females. However, in stark contrast to males, females' thermal comfort limits decrease during the RUN in comparison to the

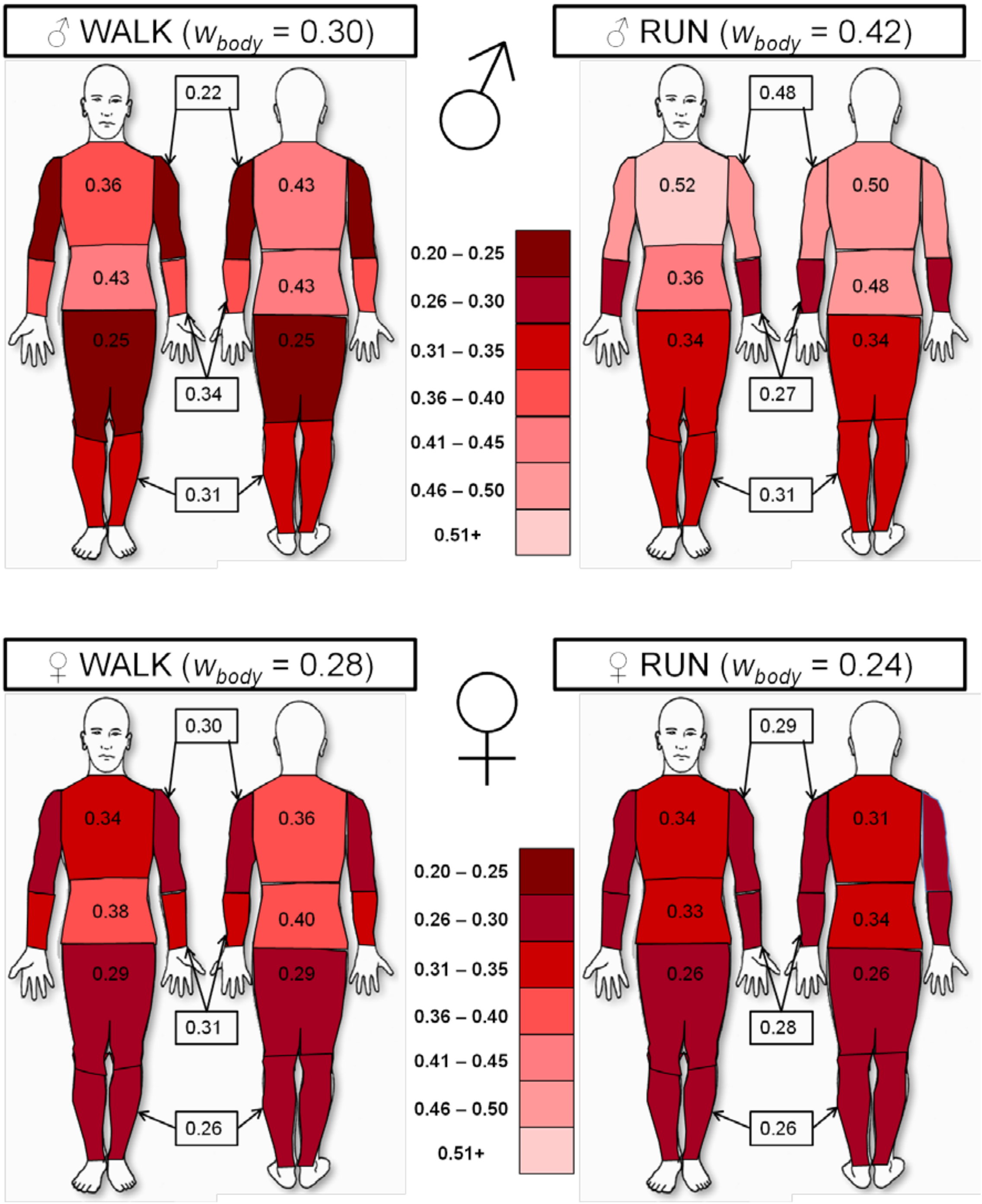


Figure 8.7: Male (♂) and female (♀) thermal comfort limits to w_{local} for each location during the WALK and RUN, which corresponds to when locations no longer felt comfortable. Whole body thermal comfort limit to w_{body} is also displayed. Lower numbers indicate higher sensitivity and are depicted with darker colours.

WALK. As a result, females have a lower thermal comfort limit than males across all regions during the RUN. Due to the large differences between male and female comfort limits during the RUN a one-way ANOVA with between subject factor was performed on the comfort limits obtained during the RUN condition. The results revealed a significant effect of gender ($p<0.05$) as the females had a significantly lower w_{local} comfort limit ($p<0.05$) than males. A significant effect of locations was also found and pairwise comparisons are displayed in Table 8.6. Overall the torso had a significantly higher comfort limit than the extremities.

Main findings:

- the thermal comfort limits to w_{local} are similar between genders during the WALK;
- the thermal comfort limits to w_{local} are significantly lower in females than males during the RUN;
- during both conditions the thermal comfort limit to w_{local} in both genders are lower (i.e. more sensitive) at the extremities than at the torso.

8.4 Discussion

8.4.1 w_{local}, ΔGSC and thermal comfort during different exercise intensities

The influence of w_{local} on thermal comfort has been reported in previous chapters and supports some of the findings in the literature (Winslow et al. 1939; Gagge et al. 1969a; Fukazawa and Havenith, 2009). Its ability to predict thermal comfort when sweat production is high has been questioned due to a ceiling effect in w_{local} as observed in Chapter 7. As a result, ΔGSC as an alternative predictor of thermal comfort was investigated. In Chapter 7, ΔGSC proved to be a stronger predictor of thermal comfort during high sweat production in male participants. All of the research surrounding the concept of *w* as a predictor of thermal comfort is limited to male participants (Fukazawa and Havenith, 2009; Umbach, 1982) or on a sample of mixed genders (Lee et al. 2011). It has been demonstrated that females are more sensitive to a warm thermal stimuli in Chapter 4 and cold stimuli by others (Golja et al. 2003). More importantly though, females have been reported to produce less sweat than males (Smith and Havenith, 2012; Fox et al. 1969, Bittel and Henane, 1975; Smith and Havenith, 2012; Havenith et al. 2008 Inuoe et al. 2005). Despite these findings, research has failed to consider any gender linked differences in sensitivity to the influence of sweat on thermal comfort (or wetness sensation). The sensitivity of females to a given level of w_{local} has not been investigated and a comparison to males is lacking in the literature. Therefore this chapter aims to determine female thermal comfort limits to w_{local}. Additionally, as females have a lower sweat production for the same absolute work rate (Frye & Kamon, 1981), the strength of the relationship between thermal comfort and ΔGSC will be compared to that with w_{local}.

In Chapter 7, w_{local} demonstrated a ceiling effect whilst discomfort continued to increase and it was suggested that this continual increase in discomfort was due to the influence of intradermal sweat as represented by ΔGSC. In the present study, it was expected that female's w_{local} would have a similar response to males, but this was not the case. A lower sweat production in females resulted in an overall lower w_{local} across all sites and thus avoided a plateau being reached. Figure 8.3 and Figure 8.2 illustrate the relationship between local thermal comfort and w_{local} and ΔGSC, respectively. According to the r^2 values in Table 8.2, thermal comfort had a stronger relationships ΔGSC ($r^2<0.90$) than w_{local} ($r^2<0.52$).

During the RUN, the relationship between thermal comfort and ΔGSC is initially the same during both conditions. There is a transition at higher level of ΔGSC and the slope between thermal comfort and ΔGSC differs between the two conditions. This may indicate an analgesic effect; where sensitivity reduces as a result of exercise. When comparing rest and exercise, sensitivity to a hot stimulus was reduced with exercise in Chapter 4. It is possible that exercise induced analgesia (EIA) is also applicable to sensitivity to sweat and is exercise intensity dependent. However, this was not observed for males, as the relationship between thermal comfort and ΔGSC was similar during both conditions. It remains uncertain as to why the response was not similar between genders.

Whilst different slopes were observed between thermal comfort and ΔGSC in the two conditions, only one slope for both conditions is observed between thermal comfort and w_{local}. This may be explained by the difference between the measurement of w_{local} and ΔGSC. Skin wettedness measures surface sweat whilst ΔGSC measures a combination of intradermal sweat and surface sweat. The extent of which ΔGSC is influenced by these two factors still remains uncertain. Additionally, ΔGSC is likely to be influence by the concentration of sodium chloride (NaCl) in sweat which is reabsorbed into the ductal walls prior to being released on the surface (Gibson and Sant'Agnese, 1963). Whether females hold more sweat within the epidermis or the concentration of NaCl differs between genders is uncertain. Further research needs to investigate the gender differences in sweat responses and how this may influence ΔGSC, w_{local} and thermal comfort.

The relationship between thermal comfort and ΔGSC was analysed separately for each condition, whilst w_{local} (and T_{sk}) from both conditions was combined prior to analysis. The results from the multiple regression are displayed in Table 8.3 and Table 8.4. The strength and significance of these regression models support their ability to predict thermal comfort. However, the validity of the comfort predictions for new data, including different ambient conditions, exercise intensities and/or clothing has yet to be confirmed. For now, these predictions are limited to the realms of this study. Both w_{local} and ΔGSC demonstrated strong relationship with thermal comfort during the WALK and RUN, but ΔGSC tended to be better. For male participants (Chapter 7), during conditions of low sweat production or when thermal discomfort is minimal both ΔGSC and w_{local} can be used as predictors of thermal comfort. When sweat production is high and thermal discomfort expected to be greater than ‘slightly uncomfortable’ ΔGSC was proposed as the better predictor. However, as females produce less sweat than males, the findings of the present study suggest that both w_{local} and ΔGSC can be used to predict female thermal comfort regardless of the expected sweat production or level of thermal discomfort.

8.4.2 Gender differences in sensitivity to sweat

Fukazawa and Havenith (2009) and Umbach (1982) originally investigated regional differences in thermal comfort sensitivity to w_{local}. This was achieved using specialised clothing garments comprised of impermeable and permeable material to manipulate $w_{local.}$ A similar test was carried out in Chapter 5 and the findings confirmed that the extremities were more sensitive than the torso region. The differences between the present study and Chapter 5 have been discussed in the previous chapter, but will be briefly discussed here. In an attempt to provide ecological validity for clothing designers, the present study aimed to assess these regional differences in uniform clothing whereby local sweat production and perceptual responses increased at a natural rate. The findings of Chapter 5 reflect the true regional differences in thermal comfort whilst the findings of the present study and that carried out on males in Chapter 7 provides a global picture of how local regions interact and influence local thermal comfort across the body.

Some interesting observations are present in the body maps in Figure 8.7. Females had a lower whole body thermal comfort limit than males during both conditions, but were only significantly lower during the RUN. The female values were within the range of 0.25-0.30 as originally claimed by Gagge et al. (1969). It was later claimed that we actually accept more sweat (w) on the surface of the skin with increasing metabolic rate (Nishi and Gagge, 1977). The findings of the present study do not support this claim as w_{body} thermal comfort limit was lower during the RUN in comparison to the WALK. This also occurred locally as the thresholds for local thermal discomfort occurred at a lower w_{local} values during the RUN, which may suggest that, with higher metabolic rates, females become more sensitive to the initial presence of sweat. However, the slope between thermal comfort and w_{local} are similar, but the initial points show some variation, which explains why differences were observed for the comfort limits during the two conditions. These initial points correspond with the start of exercise and it is possible that during this time, T_c and/or T_{sk} initially increase faster than the appearance of sweat and it was this and not w_{local} that influenced thermal comfort.

As with the previous chapter, the extremities seem to be more sensitive than areas of the torso in both genders and both conditions. However, the influence of w_{local} of other body segments has previously been shown to influence thermal comfort across the whole body. In Chapter 7 this was explained by the model of segmental interaction; the areas of the torso will naturally produce much more sweat than the extremities, that they dominate local thermal comfort across the whole body; this also applies to females. In terms of clothing design these results suggest that clothing should facilitate the evaporation of sweat from the torso in order to prevent local discomfort across the whole body.

The maximum discomfort experienced at the end of each condition is lower for females than males. Additionally, females had lower w_{local}, ΔGSC and GSL; supporting the claim that higher discomfort scores are relative to the amount of sweat produced. The pattern (of w_{local}, ΔGSC and thermal comfort) across the body was similar between genders; the legs scored the lowest discomfort votes and the back scored the highest. The torso is known to produce more sweat than the extremities (Smith and Havenith, 2011, 2012; Havenith et al. 2008). As stated earlier, past researchers have used w to predict thermal comfort limits and therefore restricted the methodology to low w_{local} and discomfort scores. To the author's knowledge this is the first experiment to compare thermal comfort over different exercise intensities and the results suggest that higher discomfort scores are relative to the amount of sweat produced.

To summarise, the original claim by Gagge et al. (1969) that whole body thermal comfort limit ranges from 0.25-0.30 is supported in this investigation for a female population. However, females become more sensitive to sweat as metabolic rate increase whilst males become less sensitive. Findings can be advanced to claim that local comfort limits range from 0.25-0.40 for females and 0.25-0.52 for males, when each segment is uniformly covered with clothing. Overall the results suggest that females are more sensitive to the initial presence of sweat than males, as indicated by lower thermal comfort limits, but as they produce less sweat than males they experience lower discomfort. The pattern of sensitivity across the body is similar between genders.

8.4.4 w_{local}, ∆GSC and wetness sensation during different exercise intensities

The lack of wet sensing receptors in human skin has resulted in a large amount of research into and hypotheses about how we sense wet skin. The change of T_{sk} that is brought about by evaporative cooling has been put forward as a theory of how we sense wetness. Bentley (1990) reported that cold temperature induced by a tight fitting garment (of even pressure) stimulated the feeling of wetness in the absence of moisture. This has also been supported by Plante et al. (1995) who noted that participants sensed the skin as being 'damper' with larger drops in T_{sk}. However, exposure to hot conditions or with exercise causes an increase in T_{sk}, sweat rate and the sensation of wetness. In the previous chapter it was concluded that a drop in T_{sk} was not necessary to stimulate the feeling of wetness. This is supported by the present study as T_{sk} increased significantly from rest to exercise and the sensation of wetness was still apparent, making it impossible to be attributed to a drop in T_{sk}. Overall wetness sensation consistently had a strong relationship with ∆GSC (r^2>0.89) and w_{local} had a moderate to strong relationship (r^2>0.58). Inconsistent relationships were found between wetness sensation and T_{sk}, which were generally weaker on the torso and higher on the extremities. Recent research by Newton et al. (2009) found that the initial perception of microclimate RH is linked to the rate of reduction of local T_{sk}. However, the present study found that exposure to hot conditions or with exercise causes an increase in T_{sk}, sweat rate and the sensation of wetness. Much of the research into wetness sensation is often associated with clothing research, under neutral conditions where fluid is applied onto the skin or changes are made in the microclimate as opposed to allowing wetness to be detected through the process of sweat production (Plante et al. 1995, Bentley, 1990; Hollies et al., 1979). As mentioned in the previous chapters, sweating causes epidermal swelling which increases the sensitivity of receptors residing in the skin (Berglund and Cunningham, 1986; Berglund, 1995, cited in Arens and Zhang, 2006, p.595). The presence of sweat on the skin and the control of an increasing T_{sk} must be regulated by different afferent inputs that enable humans to detect sweat in the skin or on the surface that is different to mechanisms that stimulate wetness sensation as described by Bentley (1990), Plante et al. (1995) and Newton et al. (2009).

8.5 Conclusions

The natural variation of physiological responses (ΔGSC, w_{local} and T_{sk}) and perceptual responses were measured in female participants and their relationships analysed. The following conclusions were made.

- In comparison to males, a lower sweat production in females resulted in an overall lower w_{local} across all sites and thus avoided a plateau being reached.
- Thermal comfort had strong relationships with both w_{local} and ΔGSC but ΔGSC ($r^2<0.90$) was stronger than w_{local} ($r^2<0.52$).
- Unlike males, w_{local} and ΔGSC can be both used as predictors of female thermal comfort during higher metabolic rates.
- Whole body thermal comfort fell within the ranges as prescribed by Gagge et al. (1969a) (0.25-0.3) and regional sensitivity ranged from 0.25-0.40.
- According to w_{local}, there are regional differences in local thermal comfort limits, which suggest that the extremities are more sensitive than the torso. This is due to the interaction of body segments; the thermal comfort in areas of naturally low w_{local}, such as the extremities, appears to be dominated by other 'wetter' areas such as the torso.
- Females are more sensitive to sweat than males as they displayed lower thermal comfort limits across all regions.
- ΔGSC suggest that discomfort and wetness sensations are relative to the amount of sweat produced for that specific body region as the torso areas scored the highest discomfort scores, which were mirrored by the highest w_{local} and ΔGSC.
- The findings of this chapter reconfirm that a drop in skin temperature is not required to stimulate a wetness sensation
- Wetness sensation had strong relationships with both w_{local} and ΔGSC, but ΔGSC ($r^2<0.89$) was stronger than w_{local} ($r^2<0.58$) and T_{sk} ($r^2<0.19$).

Chapter nine – Laboratory study 6

Galvanic skin conductance, epidermal hydration and regional sweat rate

9 Chapter Summary

The purpose of this study was to explore the measurement of galvanic skin conductance (GSC) and understand the extent to which it is influenced by pre-secretory sweat gland activity, epidermal hydration (HYD) and the amount of sweat present on the skin surface. This was achieved by exposing participants to a protocol that very slowly increased sweat production via changes in metabolic rate and ambient conditions. Eight males and eight females sat in a thermoneutral environment (23.4 ± 0.5°C, 50 ± 4.7% RH) for 10 minutes followed by 10 minutes in a warm environment (30.1 ± 1.0°C, 30 ± 4.7% RH). In the following order, participants began exercising on a treadmill at 30% $\dot{V}O_{2max}$ for 20 minutes, 50% $\dot{V}O_{2max}$ for 10 minutes and 70% $\dot{V}O_{2max}$ for 20 minutes. After exercise all participants remained in the warm condition whilst post exercise sweating response was monitored. During the protocol, ∆GSC (change from baseline in GSC) was measured continuously, whilst HYD was measured every 2.5 minutes during rest and every 5 minutes during exercise. Regional sweat rate (RSR) was measured using absorbent pads. The point at which sweat became visually present on the skin surface was also noted.

∆GSC increased immediately with heat exposure, prior to an increase in RSR, demonstrating its ability to detect presecretory sweat gland activity. HYD also increased during heat exposure prior to a response in RSR, suggesting that the skin hydrates before sweat is released onto the skin surface. HYD reached ceiling levels indicating the hydration of the stratum corneum has an upper limit when it is maximally hydrated. Beyond this, marked increases in RSR and ∆GSC occurred until the end of exercise. ∆GSC reached its maximum values during high sweat production and the data suggests that ∆GSC is predominately influenced by the amount of sweat produced and released onto the skin surface as supported by its strong correlations with RSR (r^2>0.80). From previous studies it is known that sweat only in direct contact with the electrode point influences the measurement. Sweat on the surrounding surface has no effect on ∆GSC. Post exercise responses were also monitored and RSR

decreased faster than ∆GSC and HYD. It was evident that sweat still remains within the epidermis despite a reduction in sweat production. The relationship of ∆GSC with HYD, RSR and thermal comfort were explored in each gender. Strong relationships were observed between thermal comfort and ∆GSC (r^2>0.79) and HYD (r^2>0.78) during exercise. These relationships do not follow a similar response during post exercise and it is evident that a non-thermal factor governs thermal comfort after the cessation of exercise.

9.1 Introduction

In previous chapters, ∆GSC was shown to mostly mimic RSR and skin wettedness (*w*) in response to exercise and heat exposure. It also proved to be a strong predictor of thermal comfort, particularly during high sweat production. GSC has been shown to increase prior to sweat reaching the skin surface (Darrow, 1964) and is therefore also indicative of pre-secretory sweat gland activity. GSC is suggested to be influenced by the amount of sweat produced within the glands, the skin hydration level and the amount of sweat present of the skin surface (Edelberg, 1972). The extent to which each of these contributes to the value of GSC is unknown.

Understanding the skin structure, sweat gland structure and function can enhance the knowledge of what influences GSC. The structure of the skin can be viewed in Figure 9.1, in-which there are two clear layers; the epidermis and the dermis.

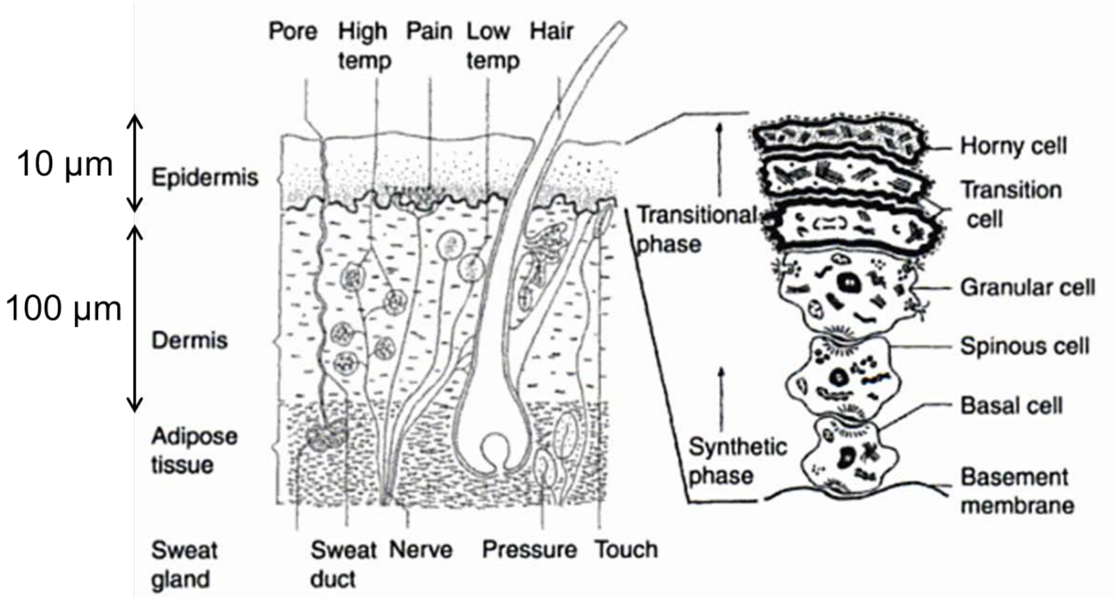


Figure 9.1: The structure of the human skin (Parsons 2003, p. 351). According to Agache and Humbert (2004) the average thickness of the skin is 120µm; the epidermis is approximately 10µm and the dermis is 100µm. The adipose tissue depends on the individual body fat.

The epidermis is the most superficial layer and consists of stratum corneum (horny layer), the stratum granulosum (granular cell), the stratum spinosum (spinous or prickle cell layer) and the stratum basale (basal cells). There is a continual generation of epidermal cells, where healthy living cells gradually moving to the surface of the skin (from the basal cell towards the transition cells) die and form a protective layer (horny cells) until they fall off (Parsons, 2003). The epidermis' has a high electrical resistance due to a thick layer of dead cells which are comprised of keratin (Edelberg, 1972). The dermis is the connective tissue compartment that provides pliability, elasticity and tensile strength.

The sweat gland structure is illustrated in Figure 9.2. The glands are tubular epithelium cells comprise five portions; the secretory portion, the intraglandular coiled duct, the intradermal 'straight' duct, and the intraepidermal spiralled duct (acrosyringium), which is separated into the sweat duct ridge and the spiralled intraepidermal portion of the duct (Abenoza and Ackerman, 1990). The secretory portion and coil (Labelled 1-2 in Figure 9.2) are located underneath the dermis in the subcutaneous layer, along with hair follicles, fine muscle filaments and blood vessels (Li, 2001). The gland extends into the intradermal straight duct, which passes through the dermis. The distal portion of the duct connects to the acrosyringium which is typically a spiralled duct that opens onto the skin surface (Sato et al., 1989a;b). The glands become active in response to rises in T_c and/or T_{sk} (McCook et al. 1965; Nadel et al. 1971) and are primarily stimulated via the release of the neurotransmitter acetylcholine from cholinergic sudomotor nerves which binds to receptors on the gland (Randall and Kimura, 1955, cited in Shibasaki et al. 2006, p.1693). Once it has bound to the receptors, intracellular calcium (Ca^{2+}) concentration increases, which causes an increase in permeability of potassium (K^+) and chloride (Cl^-) channels. This causes the release of an isotonic precursor fluid from the secretory cells (Sato et al. 1989a;b). This is referred to as the pre-secretory sweat gland activity which can be detected by changes in GSC. The fluid then passes along the duct and en route to the skin surface NaCl is reabsorbed in the ductal walls. As a result, sweat that appears on the skin surface is hypotonic relative to plasma. Previous researchers have measured the conductivity of the sweat collected as an indicator of the reabsorption capacity (Shamsuddin and Togawa, 1998). From research, it is apparent that conductance measured will not only be influenced by the amount of sweat produced, but also by the composition of the sweat (Gibson, 1963).

Before sweat is released onto the skin surface, a process known as corneal hydration occurs in which the sweat penetrates the acrosyringium due to a build up of pressure is absorbed by the stratum corneum. According to Kilgman (1964) the stratum corneum is very hygroscopic, in that it can hold up to 70% of its own weight in water. It has been postulated that the corneum hydrates first before sweat is released onto the skin surface (Boucsein, 2011). Once sweating has subsided, the glands no longer produce sweat and the sweat within the duct and acrosyringium either slowly diffuses into the stratum corneum or is reabsorbed into the sweat gland (Edelberg, 1972). The function of the sweat gland after stimulation has subsided has received comparatively little attention in comparison to the stimulation itself. This is particularly true for the measurement of GSC due the main research body that utilises GSC, which is typically psychophysiologically based.

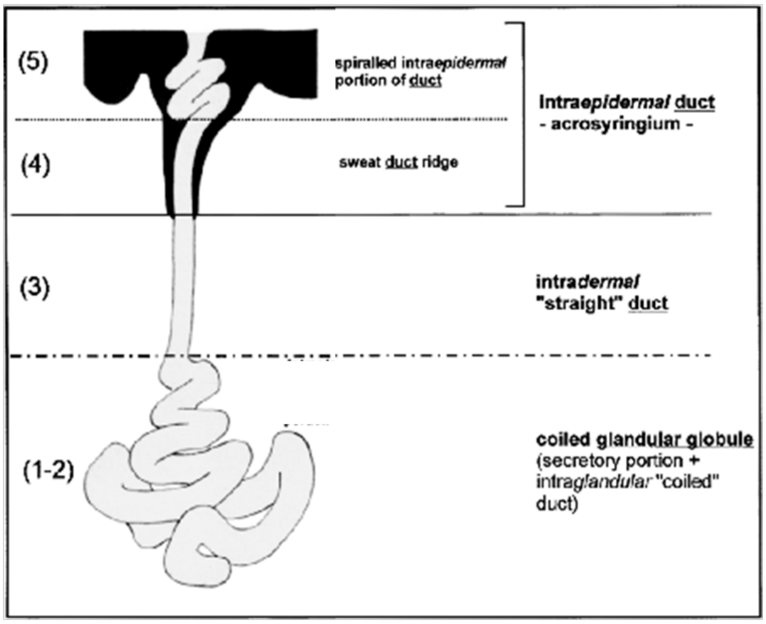


Figure 9.2: A schematic presentation of the sweat gland. The numbers on the left denote the segments of the glands; (1-2) gland, containing the secretory portion and the coiled duct; (3) intradermal duct; (4 and 5) acrosyringium, comprising the lower sweat duct ridge (4) and the upper spiralled duct (5). Modified drawing from Abenoza and Ackerman (1990, p.44).

The process from the stimulation of the sweat glands, to the appearance of sweat on the skin surface all contribute to the value of GSC. Based on the findings that GSC is only affected by surface sweat that is in direct contact with the electrode point and not by the surrounding areas an updated version of the hypothetical electrical circuit analogy model (from Chapter 6) in presented in Figure 9.3. The model illustrates areas which, according to the literature, and based on pilot studies in Chapter 6 influence GSC. In the left hand diagram, electrical resistances are drawn, representing the influence of different layers/structures on overall GSC that are illustrated in the right hand diagram; sweat coil, duct layers, stratum corneum and a skin surface layer. The electrical resistances which are considered to influence GSC are labelled on both diagrams and explained below:

- SD1 indicates the effect of pre-secretory sweat gland activity;
- D1 indicates the movement of sweat from the glands towards the surface. NaCl is reabsorbed during this process prior to the sweat reaching the skin surface;
- E2 indicates the effect of hydration of the stratum corneum;
- E1 indicates the effect of sweat on the skin surface.

The factors listed above can, to some extent, be monitored using additional tools. Epidermal hydration (E2 in Figure 9.3) is often measured in dermatological research for medical or cosmetic purposes. Various methods are used to measure epidermal hydration, but typically they are based on capacitance measurements. Capacitance based measuring devices require two metal plates separated by an insulating medium (dielectric) together forming a capacitor (Flur et al. 1999). A voltage is connected to the capacitor and electrons flow from one plate to another. The capacitor stores the electrical charges and its quantity is called the capacitance. Alterations in water content in the skin causes changes of capacitance. The measurement depth is dependent upon the geometric factors of the probes and has been reported to vary from 30µm to 100µm (Fluhr et al. 1999; Alanen et al. 2004). Stratum corneum thickness various across the body ranging from 11 to 20 µm for the shoulder and dorsal forearm and total epidermis thickness ranging from 75 to 96µm (Sandby Møller et al. 2003). According to Warner et al. (1988) a dry epidermis is 30-40µm. There are some inconsistencies regarding the thickness of the skin. Uncertainties in skin thickness and the different layers explain why the measuring tools available offer a range of measuring depths. In this chapter a Delfin Moisturemeter, which is a capacitance-based measuring device, will be used to assess the hydration of the epidermis. The measuring depth of the Moisturemeter is not constant, but dependent upon the water content in the skin. They claim that it measures the ‘effective hydration’ of the upper layers of the skin, specifically the stratum corneum taking into account its thickness (Alanen et al. 2004). Using a device to measure epidermal hydration alongside GSC may give insight into the extent of which epidermal hydration contributes to GSC and what happens once the skin is at its maximum hydration capacity.

Regional sweat rate (RSR) refers to the amount of sweat produced per unit time at a specific location on the skin and reflects E1 in Figure 9.3. It can be measured using sweat droplet analysis (Inuoe et al. 1999), ventilated capsules (Kondo et al. 2001) or absorbent pads (Smith and Havenith, 2011). Regional absorbent pads were used in the

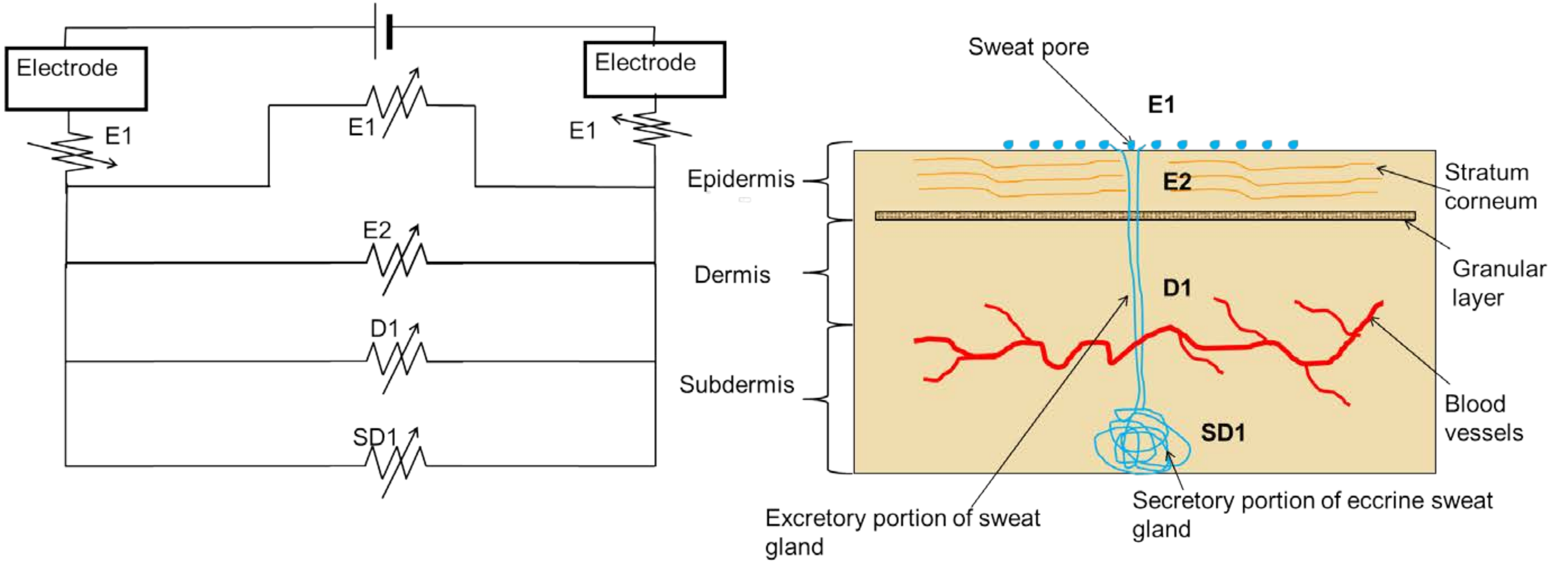


Figure 9.3: An updated version of a hypothetical electrical circuit analogy model (left). The labelled resistances correspond to the areas within the skin (diagram on the right) which contribute towards the resistance/conductance of the skin. Label E1 indicates the effect of sweat on the skin surface directly underneath electrode; E2 indicates the effect of hydration of the stratum corneum; D1 indicates sweat travelling through the duct within the skin; SD1 indicates sweat being produced within the gland.

tests research in Chapter 6 of this thesis and strong correlations were observed between GSC and RSR ($r^2>0.60$, $p<0.05$). Linking RSR, HYD and GSC may provide further information into how the process of sweat production influences GSC and the components outlined in Figure 9.3. SD1 and D1 are difficult to determine separately as they would require either invasive measurement or highly technical equipment such as optical coherence tomography which captures images of the sweat glands as they produce sweat and track its delivery to the pore. By noting the moment when sweat is visible on the skin surface and the corresponding GSC and HYD value, information regarding the pre-secretory sweat gland activity (SD1, D1 and E2) can be obtained.

To summarise, it is hypothesised that GSC is influenced by the whole process of sweat production; the filling of the sweat glands, the transfer of sweat through the dermis and epidermis and its appearance on the skin surface; areas SD1, D1, E2 and E1 in Figure 9.3. HYD is influenced by sweat located in the epidermis; area E2. RSR is influenced only by sweat on the skin surface; area E1.

9.1.2 Aims

The primary aim of the investigation is to understand the influence that each level in Figure 9.3 (SD1, D1, E2 and E1) has upon GSC during different levels of sweat production (low, medium, high and post exercise). In order to achieve these aims, sweat rate needs to be increased very slowly in order to clearly observe sweat gland activity and an increase in HYD before sweat is present on the skin surface. Secondly, the reverse of this process, the cessation of sweating will be monitored to observe if the response mirror that of sweat gland stimulation. The final aim is to understand how the process of sweating influences thermal comfort and if this differs for males and females.

9.2 Methods

The experimental methodology is outlined in Chapter 3. A summary with specific details to this experiment will be described here.

9.2.1 Participants

Eight males (height 182.9 ± 4 cm, mass 80.1 ± 9.6 kg, age 26 ± 4 yrs, $\dot{V}O_{2max}$ 54.9 ± 3.5 $ml \cdot kg \cdot min^{-1}$) and eight females (height 166.4 ± 6.7 cm, mass 62.5 ± 6.3 kg, age 24 ± 5 yrs, $\dot{V}O_{2max}$ 51.0 ± 6.8 $ml \cdot kg \cdot min^{-1}$) were recruited from the staff and student population at Loughborough University.

9.2.2 Experiment design

The aim of the investigation is to monitor HYD, RSR and the appearance of sweat on the skin surface to understand how the production of sweat and its passage through the skin influences the measured value of ∆GSC. The relationship between thermal comfort and ∆GSC, HYD and RSR will also be investigated. To achieve these aims the experiment was designed to slowly increase sweat production and ensure a high sweat rate occurred by the end of the experiment. It was also of interest to monitor the decline of the response after a large quantity of sweat was produced. For this purpose, each participant completed a pre-test session to assess fitness level and one main trial on a separate day. The relationship between ∆GSC, HYD and RSR was of primary interest.

9.2.3 Clothing

Participants dressed in the required clothing, which consisted of running shorts plus sports bra for females and their own personal socks and athletic trainers.

9.2.4 Methodology

During the first visit, participants' stature and body mass were recorded followed by a submaximal fitness test based on the Åstrand-Rhyming method (ACSM, 2006), as outlined in Chapter 3.

For the main trial, pre and post-test nude weight was recorded. Participants self inserted a rectal probe 10 cm beyond the anal sphincter and dressed in the required clothing. The following four measurement areas were chosen based on data from Smith and Havenith (2011), showing these to be areas of different sweat rate; chest, upper back, upper arm and upper leg. Each area was cleansed with deionised water and dried with sterile towels. Four pairs of pre-gelled electrodes were attached for the measurement of ∆GSC using MP35 Biopac System (Goleta, California, USA). Adjacent to each set of electrodes, a skin thermistor (Grant Instrument Ltd, Cambridge, UK) was attached to the skin using 3M^{TM} Transpore^{TM} surgical tape, (3M United Kingdom PLC). The space between electrodes was designated for the measurement of epidermal hydration (HYD) which was taken at intervals using a MoisturemeterD Compact (Delfin Technologies Ltd., Kuopio, Finland). HYD and GSC were measured as a change from baseline (∆GSC). The area just above the electrodes was designated for the collection of regional sweat rate (RSR) using 3M^{TM} Tegaderm^{TM} absorbent pads (3M Solutions, Bracknell, UK). RSR was measured using the same methodology as Smith and Havenith (2011) and as used in Chapter 6. Figure 9.4 illustrates the measurement area (of the upper back) once all equipment is in place and shows the measurement of HYD.

To gradually increase sweat production, the test was split into 3 main stages; rest, exercise and post exercise. The activity, the duration, the ambient conditions of each stage and the corresponding label are listed in Table 9.1.

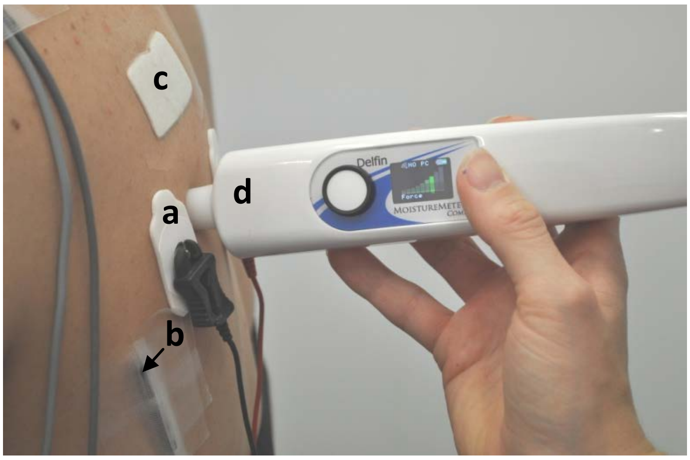


Figure 9.4: The measurement area of the upper back indicting the location of a) an electrode for ∆GSC, b) thermistors to T_{sk}, c) absorbent pad for RSR, d) moisture meter for HYD (applied periodically).

Table 9.1: The label and description of each of each stage. Exercise was carried out on a treadmill.

Label	Activity	Duration	Ambient conditions
R1	Rest	10 minutes	20°C, 40% RH
R2	Rest	10 minutes	20°C, 40% RH
EX1	Exercise at 30% $\dot{V}O_{2max}$	20 minutes	30°C, 30% RH
EX2	Exercise at 50% $\dot{V}O_{2max}$	10 minutes	30°C, 30% RH
EX3	Exercise at 70% $\dot{V}O_{2max}$	20 minutes	30°C, 30% RH
P-EX1	Post exercise rest	10 minutes	30°C, 30% RH
P-EX2	Post exercise rest	10 minutes	30°C, 30% RH

During all rest periods HYD was measured every 2.5 minutes, but during exercise, participants stopped exercising every 5 minutes for HYD to be measured. At the same time, the measurement area was checked for the presence of sweat and the time noted. If there was any sweat present on the surface at the measurement site it was wiped away with a towel before the measurement of HYD. The absorbent pads for RSR were removed and replaced into the plastic bags after each stage. Throughout each stage, thermal comfort was rated every 5 minutes. For clarity Table 9.2 breaks down each section and indicates what was measured during each stage.

Table 9.2: A breakdown of the main trial stages, the duration of each stage, the measurements taken and the time interavls of the measurement during each stage. (TC = thermal comfort). * RSR during exercise was measured for the specific time of each exercise intensity.

Stage	Condition	Duration (minutes)	Measurements	Measurement intervals
R 1	20°C, 40% RH	10	ΔGSC	Continuous
			RSR	10 minutes
			HYD	2.5 minutes
			TC	5 minutes
			T_{sk}	Continuous
			T_c	Continuous
R 2	30°C, 30% RH	10	ΔGSC	Continuous
			RSR	10 minutes
			HYD	2.5 minutes
			TC	5 minutes
			T_{sk}	Continuous
			T_c	Continuous
EX1(30% $\dot{V}O_{2max}$) EX2(50% $\dot{V}O_{2max}$) EX3 (70%$\dot{V}O_{2max}$)	30°C, 30% RH	20 10 20	ΔGSC	Continuous
			RSR	20, 10, 20* minutes
			HYD	5 minutes
			TC	5 minutes
			T_{sk}	Continuous
			T_c	Continuous
P-EX1 P-EX2	30°C, 30% RH	20	ΔGSC	Continuous
			RSR (x2)	10 minutes
			HYD	2.5 minutes
			TC	5 minutes
			T_{sk}	Continuous
			T_c	Continuous

9.2.5 Perceptual responses

Participants were introduced to the thermal comfort scale and instructed how to interpret it and score. The scale was the same used in previous chapters; a 6-point

Likert scale with intermediary values; 0 =comfortable, -2 =slightly uncomfortable, -4 =uncomfortable, -6 =very uncomfortable. Participants scored thermal comfort for their whole body and each local body region (chest, upper back, upper arms and upper legs).

9.2.6 Data Analysis

All data that was continuously recorded was averaged over every 2.5 minutes during any rest stage and over every 5 minutes during any exercise stages. Data was analysed using Statistical Package (SPSS) version 18.0. The main effect of each stage and location was analysed using a two-way repeated measures ANOVA with gender as a between subject factor. The relationship between ΔGSC, HYD and RSR was analysed using Pearson's correlation. The onset for sweat appearing on the skin surface is marked along the regression line and defined as the threshold for external sweating. The relationship between ΔGSC and perceptual responses will also be analysed using Pearson's correlation.

9.3 Results

9.3.1 Core temperature, body temperature and skin temperature

Figure 9.5a-b illustrates core temperature (T_c), body temperature (T_b), and mean skin temperature ($\bar{T}_{sk}$) and Figure 9.5c-d illustrates local T_{sk} during the experiment for males and females. All physiological responses remained stable during the rest period and increased with heat exposure until the end of exercise, after which they all declined. During the 20minute post-exercise period none of the physiological responses returned to baseline.

According to the two-way repeated measures ANOVA, there was a significant effect of stage ($p<0.05$) on T_c and T_b as they increased throughout the whole trial. A comparison of each stage was done using pairwise comparison and adjusted using Bonferroni (see Table 9.3**)**. There was a significant effect of gender as the females have a slightly higher overall T_c than males (37.65 ± 0.35°C and 37.35 ± 0.37°C, respectively, $p>0.05$) and the same was true for $T_{b.}$ There was no significant interaction between gender and stage as they both increased and decreased in a similar manner.

Two-way repeated measures ANOVA revealed no significant effect of gender for $\bar{T}_{sk}$ and local T_{sk} as they were similar between genders. A significant effect of stage was found for $\bar{T}_{sk}$ and local T_{sk} as they were higher at the end of the trial compared to

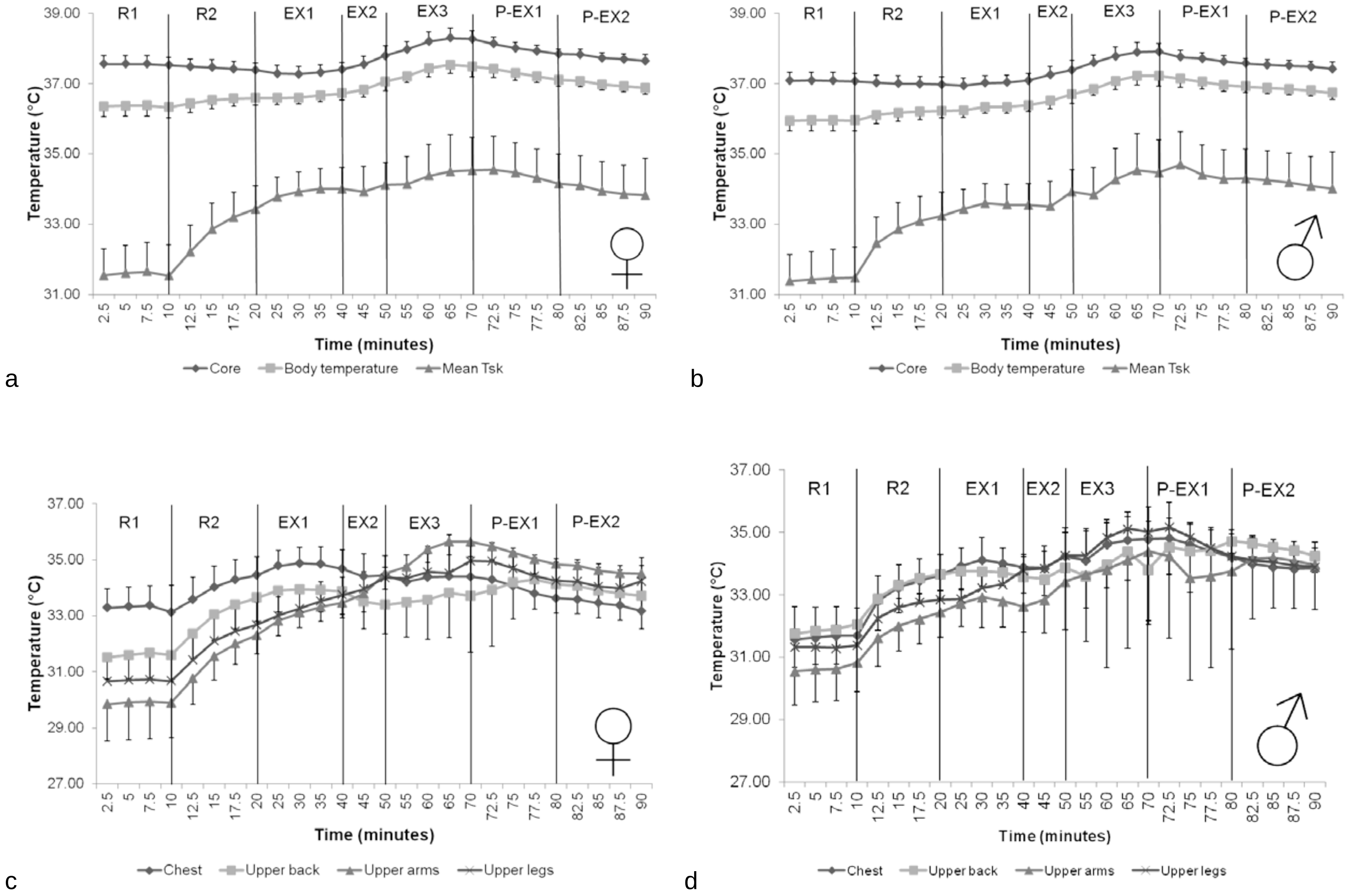


Figure 9.5: The average T_c, T_b and mean $\overline{T}_{sk}$ and c-d) local T_{sk} during the trial for females (♀) and males (♂). The vertical lines separate each stage of the trial; R1 and R2 are rest, EX1, EX2 and EX3 indicate incremental stages of exercise; P-EX1 and P-EX2 indicate post exercise stages.

baseline. A comparison of each stage was done using pairwise comparison and adjusted for multiple comparisons using Bonferroni; the results are shown in Table 9.3. R1 was significantly lower than all other conditions ($p<0.05$) and EX3 was significantly higher than R2 and P-EX2 ($p<0.05$).

Table 9.3: Significance of pairwise comparison between each stage for T_c (░ $p<0.05$ and $p<0.001$), T_b (# $p<0.05$, ## $p<0.001$), and $\overline{T}_{sk}$ (* $p<0.05$, ** $p<0.001$).

	R1	R2	Ex 1	Ex 2	Ex 3	P- Ex 1	P- Ex 2
R2	░ #**						
Ex 1	#*	#					
Ex 2	░ ##*	░ ##	▒ ##				
Ex 3	░ ##**	▓ ##	▒ #	░ #			
P- Ex 1	##*	░ #	░ #		░ #		
P- Ex 2	#*	░ #	#		░	░ #	

Main findings:

- all physiological response remained stable during the rest period and increased with heat exposure until the end of exercise;
- during the 20 minute post-exercise period all physiological responses decreased but did not return to baseline values;
- females had a significantly higher T_c than males but a similar local T_{sk}.

9.3.2 Gross sweat loss

Gross sweat loss for the females was 186.5 ± 80.9 $g \cdot m^2 \cdot hr^{-1}$ and 181.0 ± 61.5 $g \cdot m^2 \cdot hr^{-1}$ for the males (inclusive of each stage). Paired samples t-test revealed no significant difference between males and females ($p>0.05$).

9.3.3 ∆GSC, HYD and RSR during rest, exercise and post exercise

Figure 9.6 and Figure 9.7 illustrates the average ∆GSC, HYD and RSR for both females and males throughout each stage of the experiment.

Despite males having a higher RSR, ∆GSC and HYD, two-way repeated measures ANOVA with gender as a between subject factor revealed no significant effect of gender. A significant effect of stage and location was found for all measurements. Pairwise comparison of each stage is highlighted in Table 9.4 and the findings generally suggest that all variables significantly increase during each stage and significantly decrease during recovery.

For ΔGSC, regional differences were apparent in both genders, with the chest having a high ΔGSC for the females and the chest and upper back for the males. Large standard deviations are present in the female data which is due to high values obtained in two individuals. Median values were calculated as they are less influenced by large variability between participants and the results demonstrated similar regional pattern. Overall, ΔGSC of the chest and upper back was significantly higher than the upper arms ($p<0.05$). Less regional differences are evident for HYD in comparison to ΔGSC, particularly for males. Pairwise comparison revealed the HYD of the upper back was significantly higher than the upper arms ($p<0.05$). RSR of the upper back was also significantly higher than the upper arms and upper legs ($p<0.05$).

Table 9.4: Significant of pairwise comparison between each stage for HYD (░ $p<0.05$ and ▓ $p<0.001$), ΔGSC (# $p<0.05$, ## $p<0.001$), and RSR (* $p<0.05$, ** $p<0.001$).

	R1	R2	Ex 1	Ex 2	Ex 3	P- Ex 1	P- Ex 2
R2	#						
Ex 1	░ #*	░ *					
Ex 2	▒ ##**	▒ ##**	▒ ##**				
Ex 3	▒ ##**	▒ ##**	▒ ##**	░ ##**			
P- Ex 1	▒ ##**	▒ ##**	##*	*	▓ #**		
P- Ex 2	▒ ##*	▒ ##**	##	░ **	▓ # **	#*	

9.3.3.1 Rest

Resting HYD was higher for the chest and upper back compared to the upper arms and legs. During rest, all other physiological responses were relatively stable during R1 and few regional differences were observed. Although it is not clear in Figure 9.7a-b due to the scale, ΔGSC begins to increase as participants move into the chamber (R2). Two-way repeated measures ANOVA revealed that ΔGSC significantly increased from R1 to R2 (Table 9.4). ΔGSC increased prior to sweat being visually present on the skin surface as well prior to any significant increase in RSR during R1 and R2. Substantial increases in HYD were noted during R2, but this was not significantly different from R1.

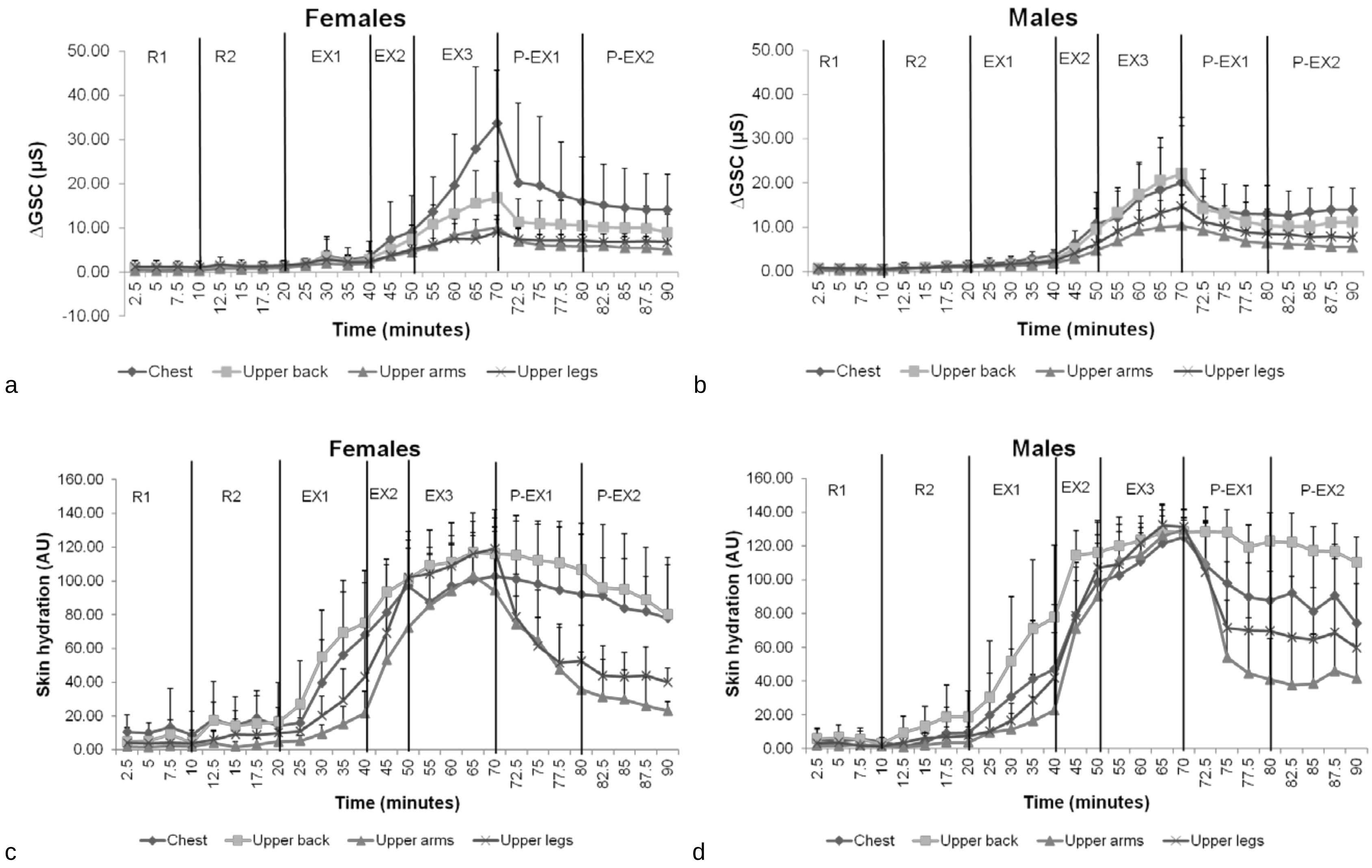


Figure 9.6: Mean (±SD) for ΔGSC (a-b) and HYD (c-d) during the whole experiment for the males and females, respectively. The vertical lines separate each stage of the trial; R1 and R2 are rest, EX1, EX2 and EX3 indicate incremental stages of exercise; P-EX1 and P-EX2 indicate post exercise stages.

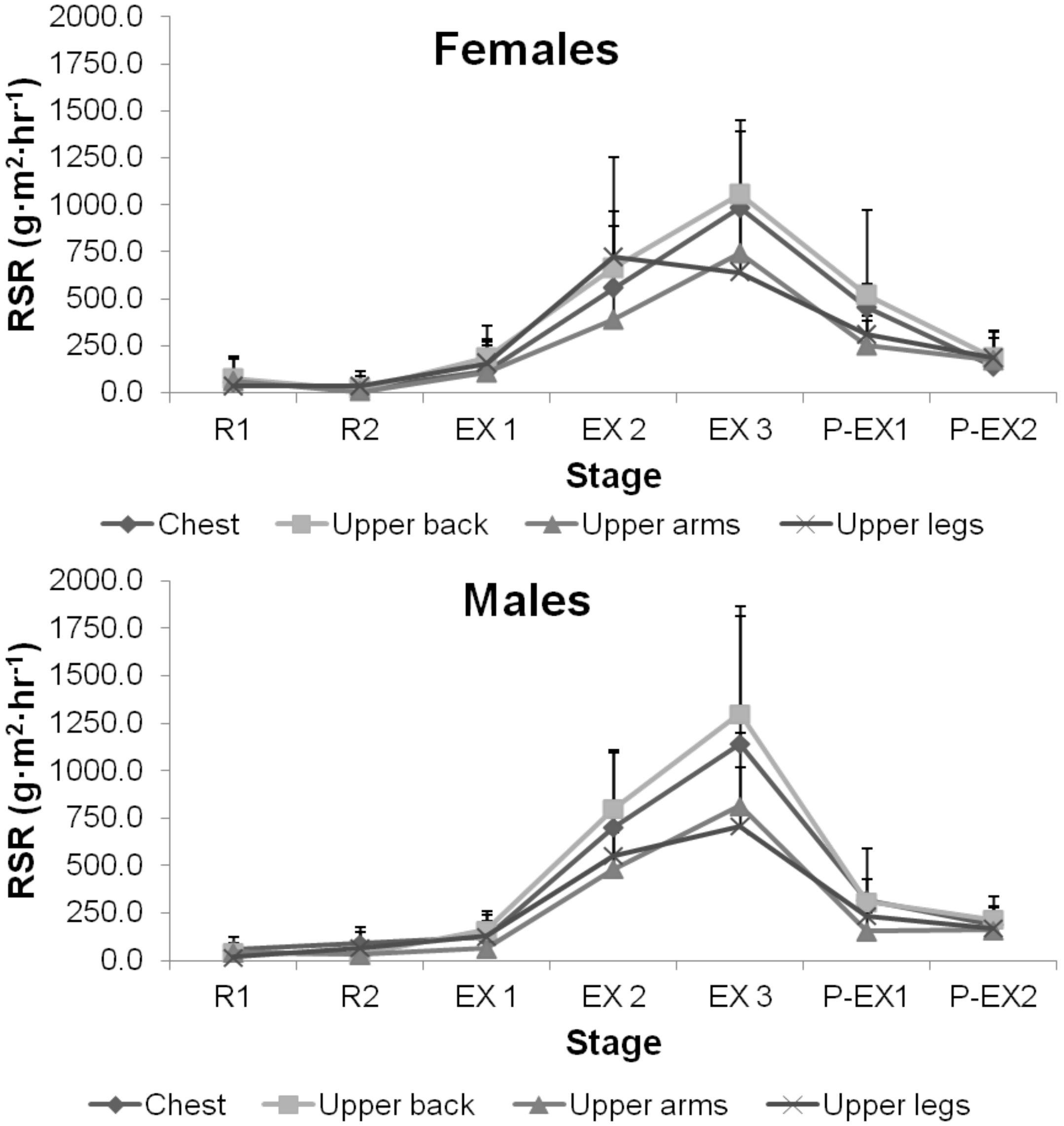


Figure 9.7: Mean (±SD) RSR during each stage for the females and males.

9.3.3.2 Exercise

From rest to exercise (from R2 to EX3), sweat production increases as confirmed by the significant increase in ∆GSC, RSR and HYD (Table 9.4). As expected, ∆GSC and RSR increased and then peaked during the final exercise stage. A ceiling effect was observed for HYD as it apparently reached its maximum capacity, which typically occurred during EX3 (Figure 9.6c-d). Once each location was noted visually as being covered with sweat, HYD tended to plateau. It was observed that locations with the highest HYD value did not always correspond with the highest RSR or ∆GSC. The continual increase in ∆GSC corresponds to an increase in RSR, although some cases a high ∆GSC did not always correspond with high RSR.

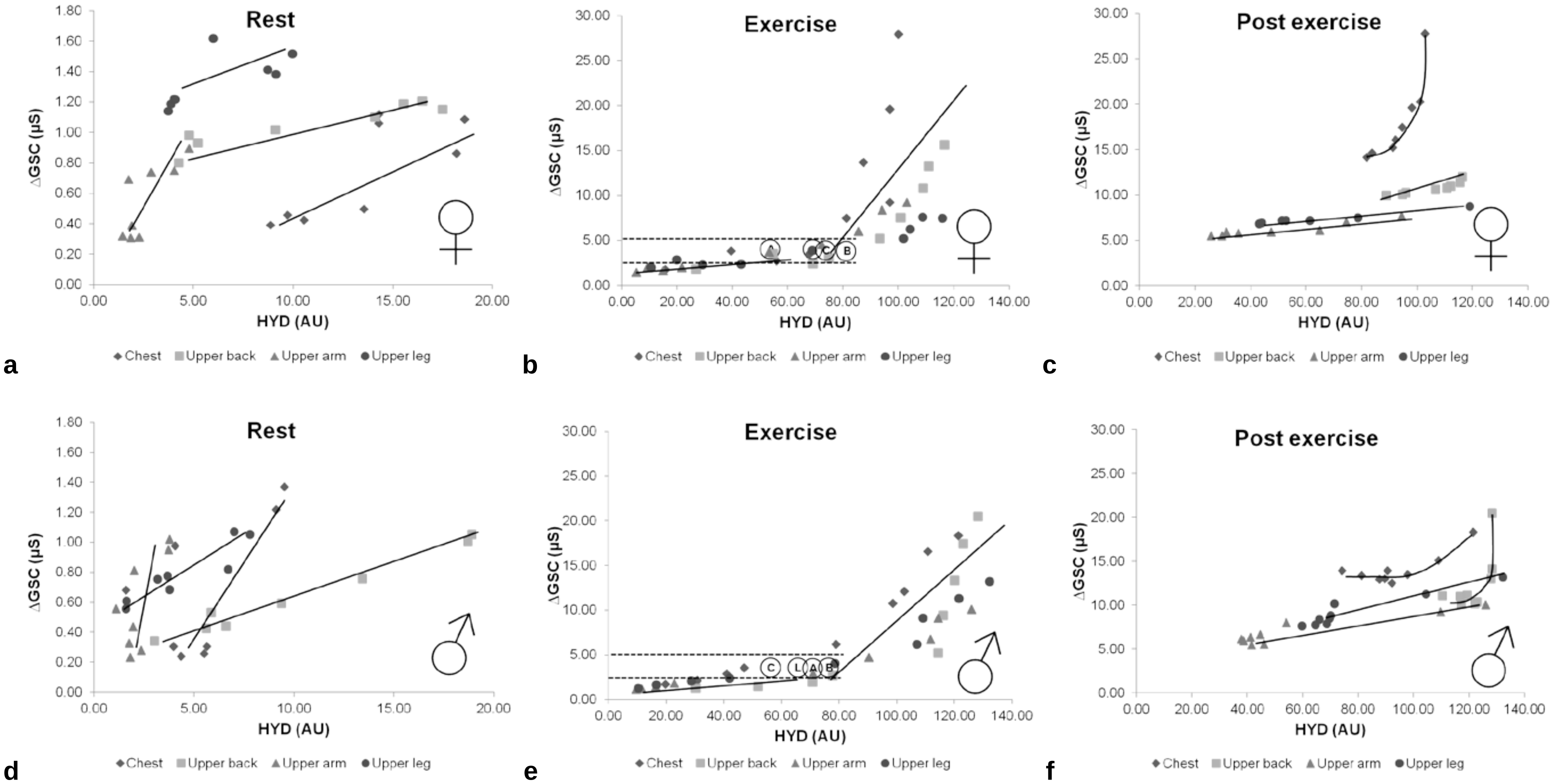


Figure 9.8: The relationship between ΔGSC and HYD during rest, exercise and post exercise for females (♀) and males (♂). Values on the x and y axis differ in graphs showing rest, exercise and post exercise to provide a clear presentation of the range of values measured. The dashed lines and letters inside circles indicate the threshold for external sweating as noted by GSC and HYD, respectively (i.e. when sweat was noted as visually being present on the skin surface at each location; A=upper arms, B= upper back, C=chest, L=upper legs).

The relationship between ∆GSC and HYD are displayed in Figure 9.8 during the three different stages; rest, exercise and post exercise. The slopes of the lines vary during rest and post exercise, but there is a threshold and slope change during exercise (Figure 9.8b and e).

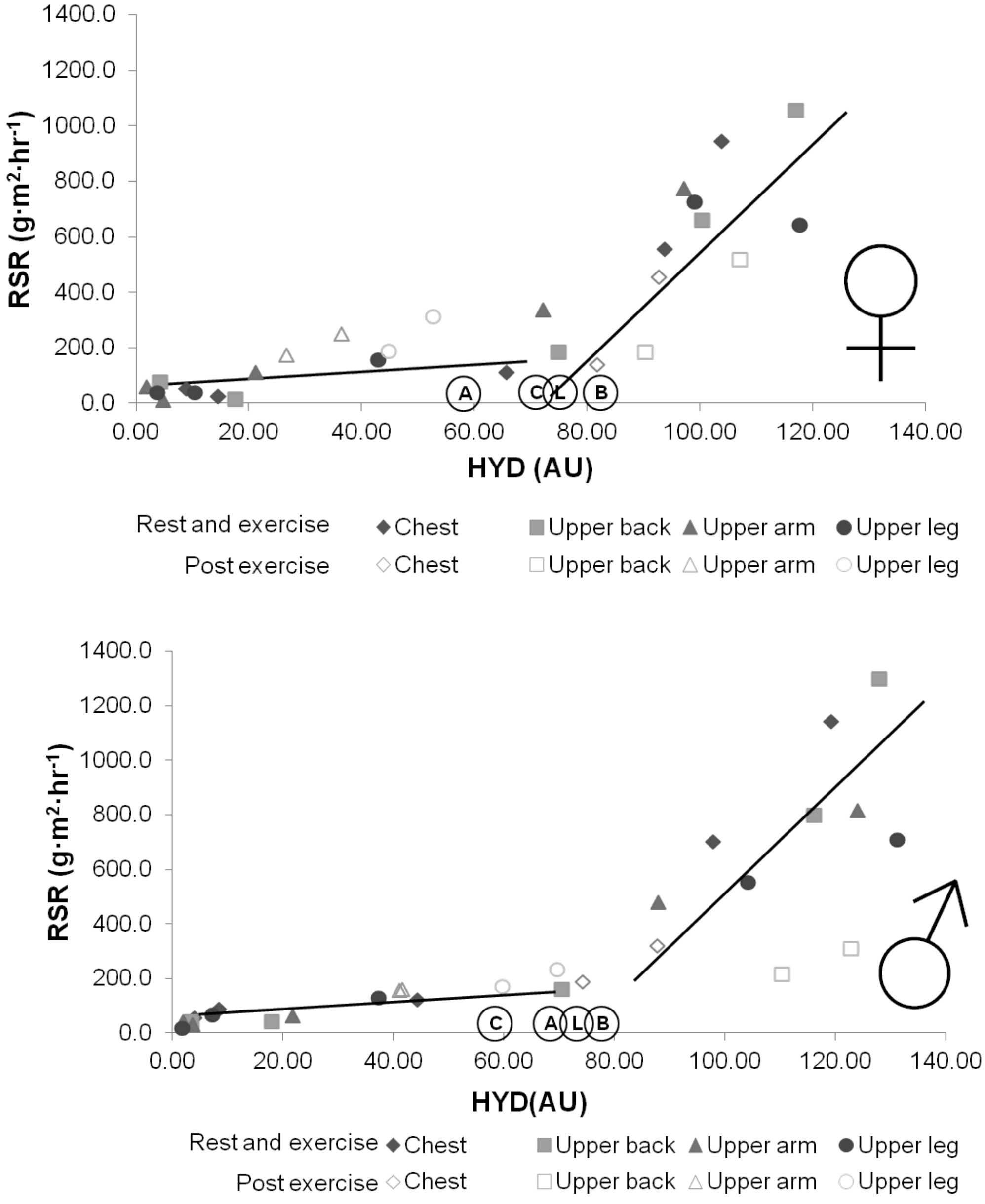
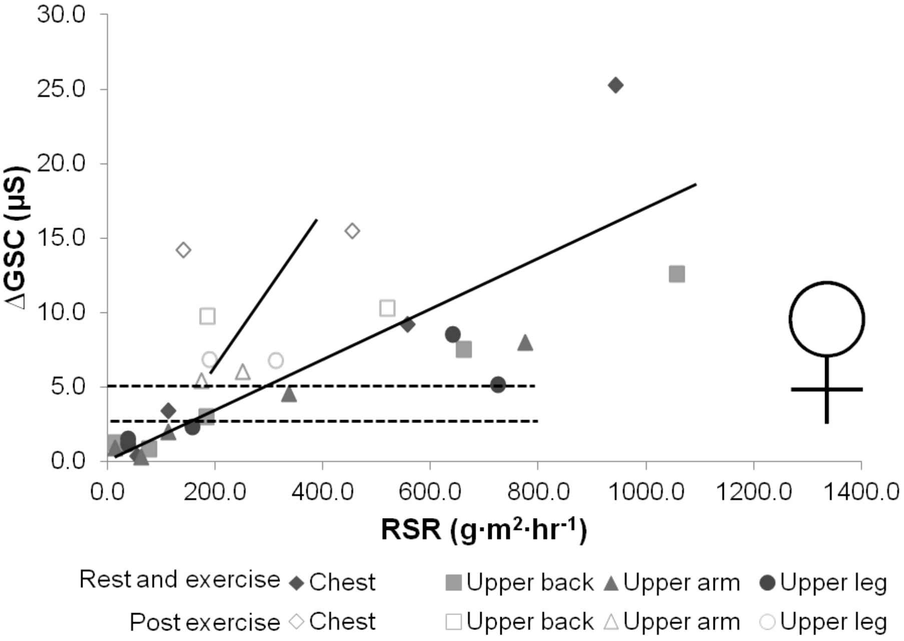


Figure 9.9: The relationship between RSR and HYD RSR for females (♀) and males (♂). Letters inside circles indicate the threshold for external sweating, i.e. when sweat was noted as visually being present on the skin surface at each location; A=upper arms, B= upper back, C=chest, L=upper legs. Filled data points indicate values measured during rest-exercise whilst unfilled date points include post exercise data only.

This is due to the ceiling effect in HYD during the final exercise stage before ∆GSC levels off. These non-linear relationships were strong for males and females at each location (at each location; chest $r^2>0.89$; upper back $r^{2>}0.96$; upper arm $r^2>0.76$; upper leg $r^2>0.69$). It is clear in Figure 9.8b and e that there is a transition in the relationship between ∆GSC and HYD at higher levels of HYD. This is represented by the two lines drawn on Figure 9.8b and e.



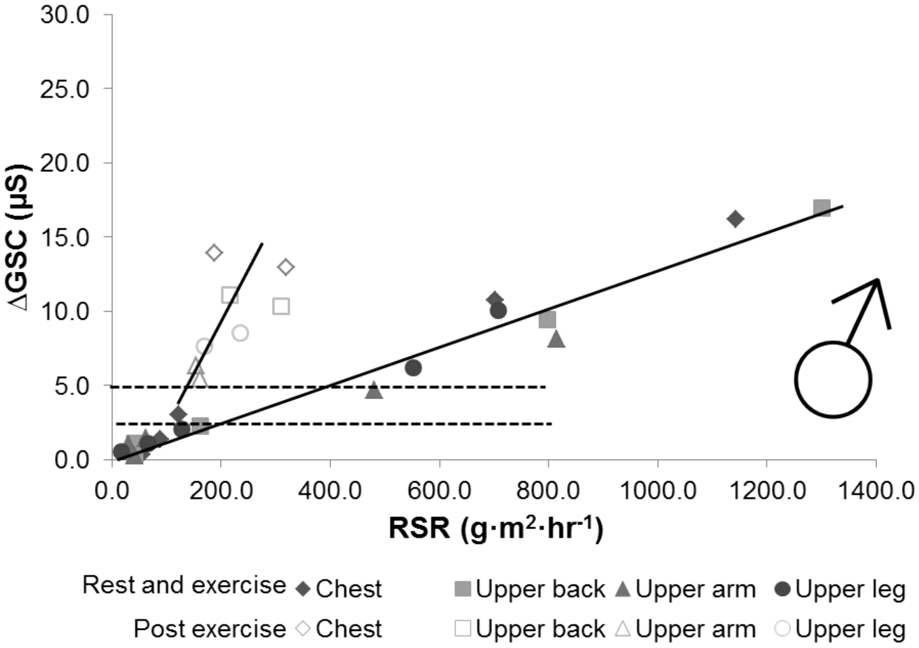


Figure 9.10: The relationship between ∆GSC and RSR for females (♀) and males (♂). Data points represent ∆GSC measured at the end of each stage and RSL measured during each stage. Filled data points indicate values measured during rest-exercise whilst unfilled date points include post exercise data only. The dashed lines indicate the threshold for external sweating for all locations, i.e. when sweat was noted as visually being present on the skin surface.

Interestingly the transition occurs when sweat was noted as being visible on the skin surface (indicated by the letter in circles on the x-axis of Figure 9.8b and e). A similar relationship is observed between RSL and HYD during exercise (Figure 9.9) at each location; chest $r^2>0.91$; upper back $r^2>0.79$; upper arm $r^2>0.98$; upper leg $r^2>0.90$, $p<0.05$). Once again a transition in the relationship between RSL and HYD, which coincides with the point at which sweat was visibly noted on the skin surface.

A strong significant linear relationship existed between ΔGSC and RSR (Figure 9.10) for females and males ($r^2>0.79$ and $r^2>0.97$, $p<0.05$, respectively) without post exercise data. The point at which sweat was visible on the skin surface was also noted and the range of values that this occurred at for each location is highlighted with two horizontal dashed lines in Figure 9.10. This typically occurred at very low values and the data points below this are all clustered at the bottom left of the graph. After this there is a large gap between the next data points.

The onset of sweat on the skin surface was assessed by the absorbent pads and also by observation of when the skin began to look moist or when sweat drops appeared on the surface. The latter was recorded and the corresponding ΔGSC and HYD noted and it typically occurred during EX 2 and EX 3. These values are displayed in Figure 9.8b and e, Figure 9.9 and Figure 9.10 and it was noted that the presence of sweat on the skin surface caused a transition in the relationship between ΔGSC, HYD and RSR. As ΔGSC and HYD produce arbitrary values the point at which sweat appeared on the skin is expressed as a percentage of the maximum values. The values indicate the threshold for pre-secretory sweat gland activity and these thresholds (raw data and as a percentage of the maximum values) are listed in Table 9.5. The ΔGSC threshold occur at a lower percentage (<39%) of its maximum value in comparison to HYD (>53%) at each location.

9.3.3.3 Post exercise rest

RSR, ΔGSC and HYD all started to decline post exercise, but did not return to baseline values during the rest period. RSR decreased at a faster rate than ΔGSC and HYD as shown by the unfilled data points in Figure 9.10. For both genders, the decline in HYD was more prominent at the extremities than the torso. For the females, HYD of the chest and upper back very slowly decreased, as did the chest for the males. HYD levelled off during the second stage of recovery, but remained higher than baseline. Due to the levelling off in HYD an exponential relationship existed between ΔGSC and HYD, similar to that during exercise (Figure 9.8c,f).

Table 9.5: Individual onset for sweat appearing on the surface and the corresponding ΔGSC and HYD level expressed as the raw data and as a percentage of its maximum of the chest (CH), upper back (UB), upper arm (UA) and upper leg (UL). Incomplete data was obtained for P10.

		Raw data								Relative to maximum values							
		ΔGSC (µS)				HYD (AU)				ΔGSC (%)				HYD (%)			
		CH	UB	UA	UL	CH	UB	UA	UL	CH	UB	UA	UL	CH	UB	UA	UL
Males	P1	1.25	1.51	1.51	2.05	27.8	22.8	12.4	7.5	17.5	13.8	17.7	17.0	34.4	16.9	13.9	6.2
	P2	4.1	2.8	3.77	4.02	106.1	126.5	98.9	120.1	13.6	13.4	58.6	19.4	87.6	90.7	67.8	83.3
	P3	4.97	3.6	3.18	3.96	68	63.2	14	19.3	44.6	34.8	27.1	38.9	51.4	44.8	9.9	14.1
	P4	4.23	2.44	2.62	2.2	65.1	70.1	110.2	110	23.6	15.6	40.0	26.8	64.4	67.3	90.9	90.9
	P5	2.5	2.24	5.26	2.23	24.8	66	83.4	77.5	7.5	7.8	62.1	15.5	22.8	53.9	71.0	59.0
	P6	2.17	2.12	4.38	4.84	20.8	122.1	128.7	104.4	8.3	6.4	29.6	28.1	15.1	83.6	87.7	68.5
	P7	3.92	1.78	5.66	3.35	100.4	104	98.2	101.7	37.5	5.2	27.3	25.9	69.5	70.2	76.0	80.9
	P8	2.68	1.64	1.26	3.12	52.8	39.4	12.8	61.5	10.1	6.2	7.4	13.9	40.6	32.9	9.7	41.3
	Mean	**3.22**	**2.26**	**3.45**	**3.22**	**58.22**	**76.76**	**69.82**	**75.25**	**20.3**	**12.9**	**33.7**	**23.2**	**48.2**	**57.5**	**53.4**	**55.5**
Females	P9	2.46	1.03	3.16	2.28	84.4	70.2	22.9	68	7.2	6.7	30.4	24.1	63.3	53.7	16.9	48.8
	P10					92.9	92	70.7	101.8					87.7	91.1	71.9	77.2
	P11	0.91	0.31	3.84	6.06	66.8	59.4	53.5	99.6	4.3	1.8	36.6	56.8	72.0	50.8	49.5	72.4
	P12	8.46	9.26	8.46	3.41	101.3	96.2	23.5	49.9	12.2	62.2	69.1	27.9	76.6	85.7	36.9	48.0
	P13	7.04	7.42	3.89	4.35	79.2	84.5	65.7	88.9	11.7	33.3	36.3	29.1	47.7	57.2	50.7	66.5
	P14	5.31	5.84	4.57	4.35	89.7	117.4	100.6	90.6	17.9	22.1	59.6	33.9	85.7	77.0	79.5	71.6
	P15	3.4	5.51	5.49	3.44	43	61.5	83	80.7	29.0	57.1	49.8	44.8	65.2	82.6	79.0	75.6
	P16	1.14	1.38	1.7	1.34	57.1	70.4	33.2	31.2	22.8	24.2	41.8	19.3	81.3	60.0	40.8	28.6
	Mean	**4.10**	**4.39**	**4.44**	**3.60**	**76.80**	**81.45**	**56.64**	**76.34**	**15.0**	**29.6**	**46.2**	**33.7**	**72.4**	**69.8**	**53.2**	**61.1**
	Mean	**3.64**	**3.26**	**3.92**	**3.40**	**67.51**	**79.11**	**63.23**	**75.79**	**17.9**	**20.7**	**39.6**	**28.1**	**60.3**	**63.7**	**53.3**	**58.3**
	SD	2.16	2.58	1.87	1.25	28.03	29.18	39.15	33.73	11.7	18.7	17.5	11.7	22.9	21.4	28.8	25.1

Main findings:

- ∆GSC and HYD increased with heat exposure, prior to an increase in RSR;
- ∆GSC and RSR continued to increase during exercise, whilst HYD levelled off during the final exercise stage in the heat;
- the presence of sweat on the skin surface caused a transition in the relationship between ∆GSC, HYD and RSR;
- areas of high RSR do not necessarily have the highest ∆GSC or HYD value;
- HYD decreased post-exercise but the response was much slower at the torso compared to the extremities;
- RSR decrease faster than ∆GSC and HYD but none returned to baseline during the 20 minute rest period;
- strong correlations were observed between ∆GSC, HYD and RSR (r^2>0.69).

9.4 Discussion

With reference to the electrical resistance model for ∆GSC presented in Figure 9.3, the primary aim of this investigation is to understand the influence that each of the following resistance levels has upon the measurement of ∆GSC; SD1, D1, E2 and E1. As these cannot be measured directly, it was attempted to assess them by comparing ∆GSC to HYD and RSR over different sweat rates; low, medium, high and post exercise. The main findings will be discussed here.

9.4.1 The process of sweating as measured by ∆GSC, HYD and RSR

9.4.1.1 Pre-secretory sweat gland activity

In Figure 9.3, SD1 refers to the subdermis which contains the sweat glands. They are said to be stimulated in response to a rise in T_c and or T_{sk} (McCook et al. 1965; Nadel et al. 1971) and according to the data T_c, T_b and $\bar{T}_{sk}$ remained stable for both genders during the initial rest period (R1). ∆GSC and HYD also remained stable during this period (see Figure 9.6a-d). Movement to a warm chamber induced an increase in ambient temperature of ~7.0°C and as a result T_c initially dropped whilst mean T_{sk} increased. The drop in T_c and rise in mean T_{sk} is typical of the core-to-periphery re-distribution of heat upon initial exposure to hot conditions or with exercise (Kenny et al., 1997). Changes to the thermal state of the body result in the release of the neurotransmitter acetylcholine from cholinergic sudomotor nerves which bind to receptors on the gland (Randall and Kimura, 1955, cited in Shibasaki et al. 2006, p.1693). Once it has bound to the receptors, intracellular calcium (Ca^{2+}) concentration increases, which causes an increase in permeability of potassium (K^+) and chloride

(Cl^-) channels and causes the release of an isotonic precursor fluid from the secretory cells (Sato et al. 1989a;b). This is referred to as the pre-secretory sweat gland activity which was detected by an increase in ΔGSC immediately upon exposure to the hot condition. Due to the scale used in Figure 9.6a-b this is difficult to see. The ΔGSC values at which this occurs are small in comparison to the range during heavy sweating, but the findings do confirm the influence of sweat within the glands and epidermis on ΔGSC. This supports previous research, which has utilised conductivity measuring devices as an indicator of pre-secretory sweat gland activity (Darrow, 1964; Johnson and Landon, 1965; Caldwell et al. 2011).

9.4.1.2 The transfer of sweat towards the skin surface

Once the sweat glands become active, sweat passes along the duct and en route to the skin surface NaCl is reabsorbed in the ductal walls. The experiment was designed to slowly increase sweat production so each stage outlined in Figure 9.3 could be distinguished by the various measuring devices used. In most cases RSR did not increase from R1 to R2 therefore the initial increase in ΔGSC and HYD are associated with pre-secretory sweat gland activity and sweat within the skin, otherwise labelled as SD1, D1 and E2 in Figure 9.3. Ideally, an increase in ΔGSC prior to an increase in HYD was particularly important for distinguishing between SD1 to E1 in Figure 9.3. This was difficult to obtain as it only occurred at the chest and upper arms during the male trials. This may be a result of the fast response time of sweat gland stimulation and sweat travelling towards the epidermis, which was not tracked by the Moisturemeter due to the length of time between each measurement (2.5 minutes). It may also be related to the measuring tool used to assess epidermal hydration and its measurement depth. The measuring depth of the Moisturemeter is not constant but dependent upon the water content in the skin. The manufacturers claim that it measures the ‘effective hydration’ of the upper layers of the skin, specifically the stratum corneum taking into account its thickness (Alanen et al. 2004). Without knowing the actual measuring depth and the variability between subjects in skin thickness, it is assumed that the Moisturemeter indicates hydration of the stratum corneum, labelled E2 in Figure 9.3. The quick response time in sweat gland stimulation (SD1) and stratum corneum hydration (E2) meant it is difficult to ascertain the influence D1 on ΔGSC. Future research should ideally continually measure HYD of the skin.

9.4.1.3 Sweat within the epidermis

Before sweat is released onto the skin surface, a process known as corneal hydration occurs in which the sweat penetrates the acrosyringium due to a build up of pressure and is absorbed by the stratum corneum (upper layers of E2). Epidermal hydration

(HYD) increased during the rest period in the heat either at same time as an increase in ∆GSC or during the next measurement sample (2.5 minutes into R2). The increase in ∆GSC and the delayed response in HYD can be attributed to sweat gland activity (SD1) and sweat travelling through the gland in the dermis (D1). The results suggest that the epidermis gradually hydrates, but has a maximum capacity as shown by a ceiling effect during the latter stages of exercise. Boucsein (2011) claimed that the corneum hydrates first before sweat is released onto the skin surface. The findings of the present study showed that RSR increase prior to the plateau in HYD, which suggests that the corneum does not have to be maximally hydrated for this to happen.

9.4.1.4 Sweat on the skin surface

As the epidermis hydrates, sweat appeared on the skin surface. The threshold for external sweating was identified for each participant and the corresponding HYD and ∆GSC were noted. The values below the threshold (for HYD and ∆GSC) indicate 'internal sweating' i.e. when sweat is produced but has not appeared on the skin surface. The threshold typically occurred during EX1 or EX2 for both males and females, which coincided with an increase in RSR. The HYD and ∆GSC thresholds for external sweating are illustrated in Figure 9.9 and Figure 9.10. There is a clear transition in the slope of the relationship between RSR and HYD. The continual increase in HYD as RSR increase suggests that either HYD is not at its absolute maximum or the measurement is influenced by surface sweat. As HYD and ∆GSC produce arbitrary values, the threshold for the appearance of sweat was calculated as a percentage of its maximum and the values are presented Figure 9.9. The threshold for HYD occurs at a higher percentage of its maximum level as it most likely represents the hydration of the epidermis (E2) and potentially the dermis (D1), whereas ∆GSC is indicative of SD1 to E1.

The exercise intensity progressively increased causing a rise in T_{sk} and T_c and thus significant increases in RSR and ∆GSC. During the exercise stages it is assumed that all components of the electrical circuit analogy model in Figure 9.3 are active. Strong significant linear relationship were found between local ∆GSC and RSR (Figure 9.10 c-d) for females and males ($r^2>0.79$ and $r^2>0.97$, $p<0.05$, respectively). This supports previous research which suggests that GSC is strongly related to increasing and decreasing number of active sweat glands (Thomas and Korr, 1957). The chest and upper back have higher ∆GSC and RSR which coincides with literature reporting high sweat rates at the torso in comparison to the extremities (Smith and Havenith, 2011; Havenith et al., 2008; Cotter et al. 1995; Hertzman, 1957). In Figure 9.7a, ∆GSC during EX3 was highest at the chest and exceeded that of the upper back, yet RSR was similar between sites. In situations where the difference in ∆GSC between locations is not mirrored by differences in RSR may be attributed to a higher NaCl content for a given sweat output.

The highest ∆GSC values measured were obtained during the final exercise periods when sweat production was at its highest. Evidently ∆GSC is strongly influenced by surface sweat, but findings from previous studies in this thesis have demonstrated that it is only the sweat in direct contact with the electrode point that influences the measurement. Sweat on the surrounding area and between the electrodes will have no effect on ∆GSC.

9.4.1.4 Cessation of sweating

Once exercise has ceased it is assumed that sweat is no longer produced by the glands (SD1). This was represented by a sudden decrease in ∆GSC immediately upon the cessation of exercise. Sweat within the duct and acrosyringium will either slowly diffuse into the stratum corneum or is reabsorbed into the sweat gland (Edelberg, 1972). At the extremities, epidermal hydration decreased immediately which suggests the sweat did not diffuse into the stratum corneum, but perhaps that the glands reabsorbed the sweat or it evaporated. The findings suggest that the higher the ∆GSC value during exercise, the larger the drop, as was seen with the upper back and the chest in both genders. Despite larger decrements in ∆GSC at these locations, HYD decreased at a much slower rate there than at the extremities. The higher HYD value at the chest and back suggest that E2 remains hydrated and that the reduction in ∆GSC is associated with a reduction of sweat in SD1, D1 and E1 in Figure 9.3. Sweat on the skin surface (E2), as measured by RSR, immediately decreased but did not return to baseline levels during the measured rest period. The time required for the sweat produced to either be evaporated from the skin or reabsorbed by the glands is an influential factor on the presence of surface sweat and epidermal hydration post sweating. Skin temperature, ambient temperature and relative humidity would also have an influential role on this process.

A limitation to ∆GSC is that the electrodes remain in contact with the skin and thus any sweat produced underneath cannot be evaporated. As sweat production decreases, ∆GSC will not return to baseline values as any sweat formerly produced will be contained within the electrodes contact point. After a quick decline post exercise, ∆GSC remains stable while HYD measured in an uncovered area with free evaporation continued to decline. In this case, it is possible that the sweat within E2 is being reabsorbed into the sweat glands; however no marked changes in ∆GSC were noted. It is also possible that the sweat within E2 is being evaporated as this is exposed to the ambient air, unlike the areas underneath the electrodes or absorbent pads. This is supported by the findings in the Chapter 6, which found that spraying artificial sweat onto the skin surface did not influence ∆GSC yet when the sweat made contact with the electrodes ∆GSC substantially increased.

9.4.1.5 Summary of findings

Based on the collective findings of this chapter, Table 9.6 indicates the process of sweat production and its corresponding label in Figure 9.3 and suggests whether they are monitored by HYD, ∆GSC and RSR.

Table 9.6: A summary of the sweat response and its corresponding label in Figure 9.3 and whether these can be measured by HYD, GSC or RSR. The level of certainty is illustrated with the number of circles (─ =no effect, ●=potentially, ●●= most likely, ●●● = almost certain).

Label	Sweat response	HYD	∆GSC	RSR
SD1	Pre-secretory sweat gland activity	●	●●●	─
D1	Sweat travels through the dermis	●●	●●●	─
E2	Sweat in the epidermis	●●●	●●●	─
E1	Sweat released onto the skin surface	●●	─	●●●
E1	Sweat on the surface in direct contact with the electrodes	─	●●●	─

SD1 reflects the stimulation of sweat glands and the production of sweat and this was detected in the immediate increase in ∆GSC upon exposure to the hot condition. Due to the uncertainty of the measuring depth of the Moisturemeter and the concomitant increase in HYD with GSC with heat exposure, HYD may measure sweat within D1. Once the sweat glands become active, sweat passes along the duct (D2) towards the epidermis (E2). A slightly delayed response in HYD was noted at some locations, which can be attributed to the delivery of sweat from the glands towards E2 (stratum corneum). In most cases RSR did not increase during the rest periods, therefore the initial increase in ∆GSC and HYD is associated with pre-secretory sweat gland activity and sweat within the skin, labelled as SD1, D1 and E2 in Figure 9.3. However, not having a constant measure of HYD made it difficult to ascertain the influence of D1 on ∆GSC. Before sweat is released onto the skin surface, the epidermis hydrates (E2) due to a build up of pressure in the acrosyringium; this caused a marked increase in RSR. These findings suggest that the stratum corneum does not have to be maximally hydrated for sweat to appear on the surface. HYD levelled off, indicating that stratum corneum hydration has an upper limit and it is at (or close) to its maximum capacity. At this point RSR and ∆GSC markedly increase and any increase in ∆GSC beyond this is predominately influenced by E1. When sweat is being produced in large amounts, ∆GSC values will be very high especially in comparison to pre-secretory responses and during epidermal hydration. Information from previous studies in this thesis suggests it is only the sweat in direct contact with the electrode point that influences the measurement. Sweat on the surrounding area will have no effect on ∆GSC.

9.4.2 The relationship between thermal comfort, ∆GSC and HYD

Although not the primary aim of this chapter, the relationship between thermal comfort and ∆GSC and HYD provides some interesting findings worthy of discussion.

∆GSC was originally investigated in this thesis based on the theory that epidermal swelling as a result of sweat production increases sensitivity of the receptors in the skin. This theory is supported by the strong correlations found between thermal comfort and ∆GSC (r^2>0.79, exponential) and HYD (r^2>0.78, linear) when post exercise data is excluded (see Figure 9.11). ∆GSC and HYD begin to increase prior to sweat reaching the skin surface and a strong linear relationship between thermal comfort and ∆GSC and HYD is observed at low levels of sweat productions in both genders. The relationship between thermal comfort and ∆GSC is exponential in both groups whereas with HYD it displayed a linear relationship as both variables levelled off at the same time. The exponential relationship between thermal comfort and ∆GSC suggests that the initial increase in ∆GSC, which is associated with epidermal hydration, is closely related to thermal comfort yet as sweat is produced and RSR increases thermal comfort is less influenced. It is possible that thermal comfort is influenced by sweat during the initial periods of sweat production where evaporative heat loss maintains heat balance, but beyond a certain point it is unlikely to be influenced by how much sweat is produced and other factors such as core temperature play a more influential role.

Another reason as to why ∆GSC was investigated is due to the ceiling effect that occurred in *w* at high levels of sweat production while a continual increase in thermal discomfort was observed. In previous chapters (7 and 8), higher whole body thermal discomfort scores were reached (-4) in comparison to the present study (-3). In Chapters 7 and 8, ∆GSC always had a strong linear relationship with thermal comfort yet in this chapter it has an exponential relationship as thermal comfort plateaued whilst ∆GSC increased. The main difference between this trial and that in Chapters 7 and 8 is the clothing worn by the participants. In the current study, participants were nude whilst in previous experiments participants wore a 100% polyester long sleeved

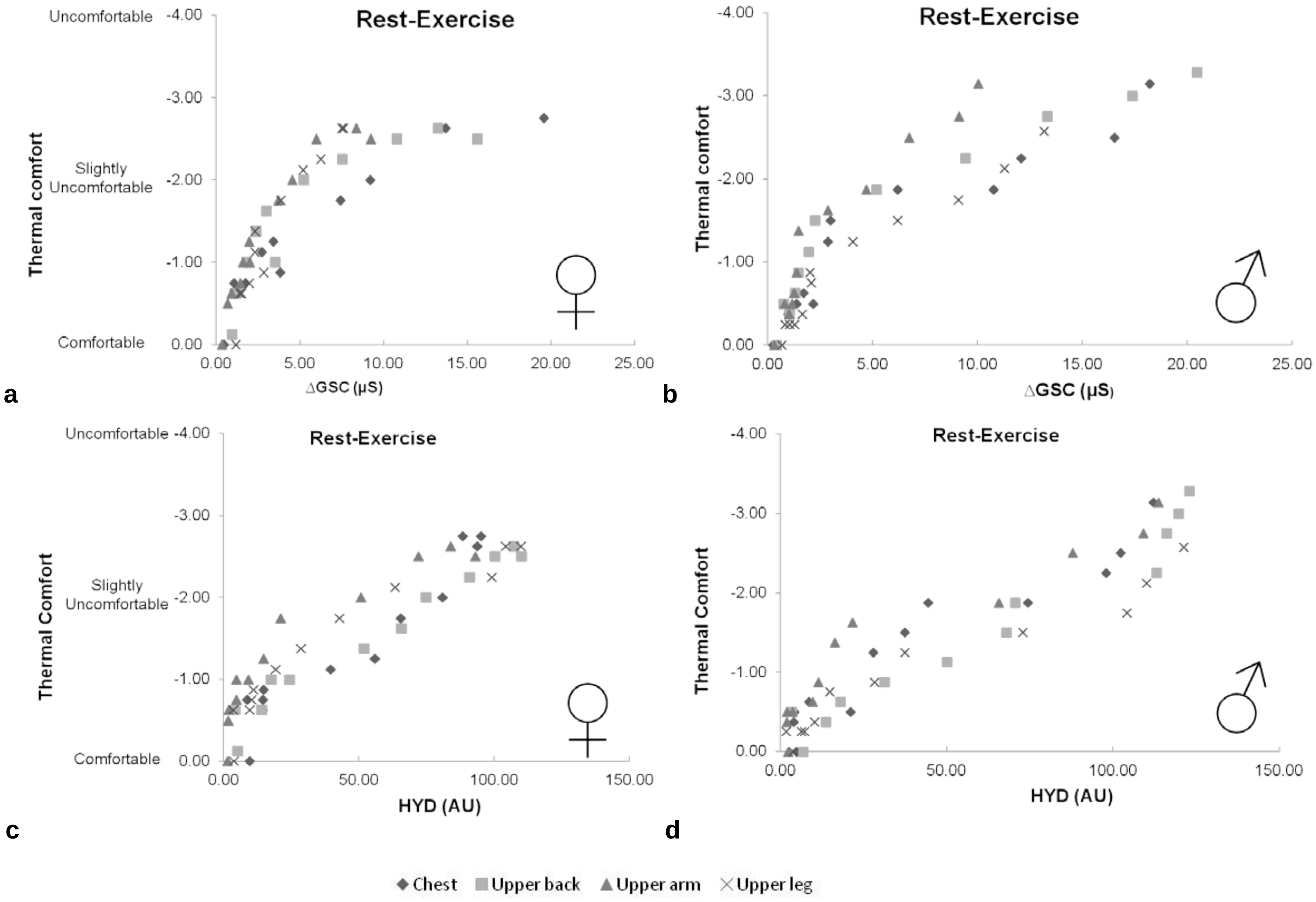


Figure 9.11: a-b) Illustrates the relationship between thermal comfort and ∆GSC measured during rest and exercise (inclusive); c-d illustrates the relationship between thermal comfort and HYD during rest and exercise (inclusive) for females (♀) and males (♂).

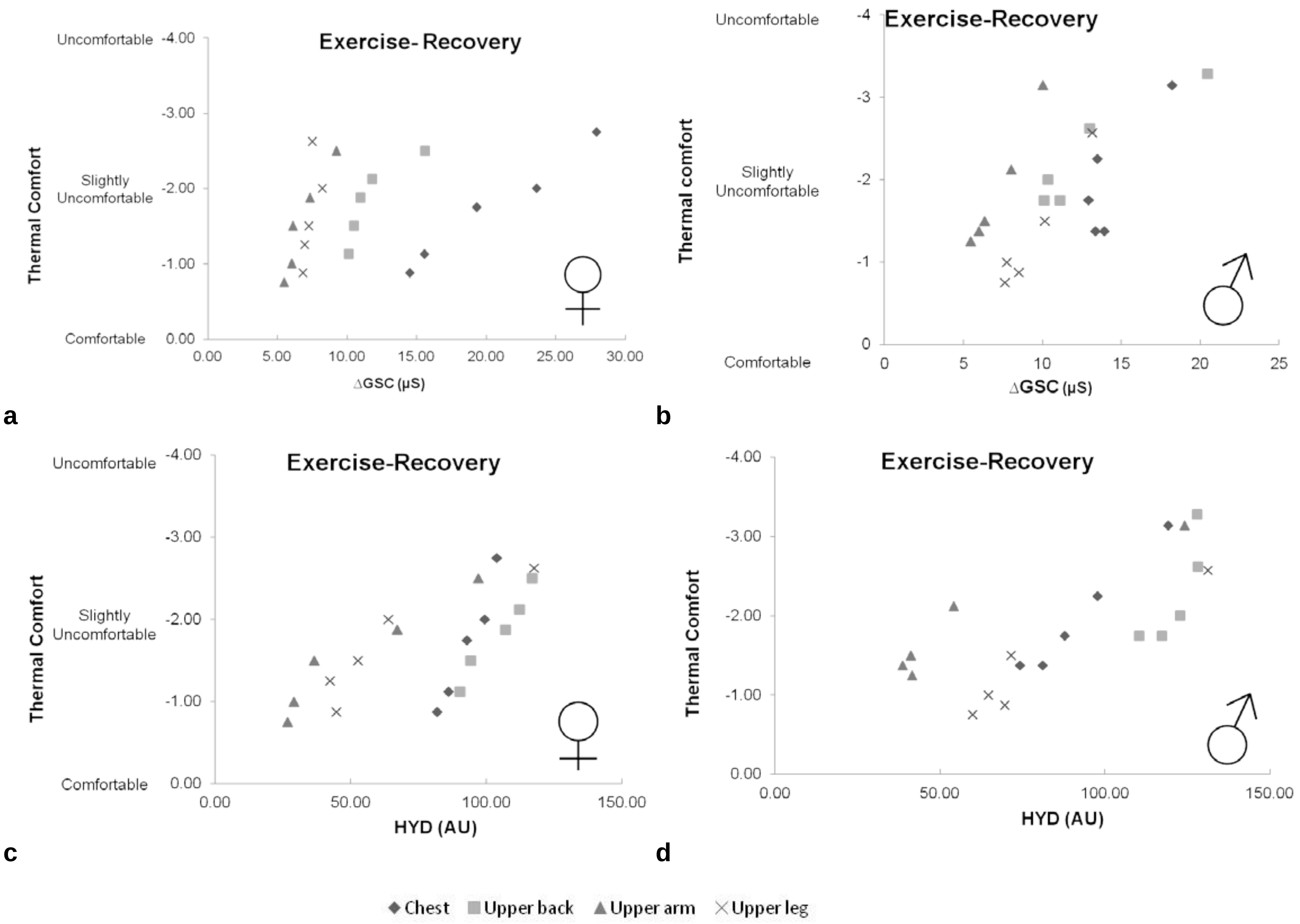


Figure 9.12: a-b illustrates the relationship between thermal comfort and ΔGSC from the last data point measured during exercise and the recovery period; c-d illustrates the relationship between thermal comfort and HYD from the last data point measured during exercise and the recovery period for females (♀) and males (♂).

clothing ensemble. This may suggest that the skin-fabric interaction influences thermal comfort during exercise in the heat as clothing absorbs moisture and heat from the body. When nude, the influential factors on perceptual responses are related to the physiological changes as ambient conditions were stable. However, wearing clothing whilst exercising may cause a skin-fabric interaction that stimulates a variety of mechanical receptors (Li, 2001).

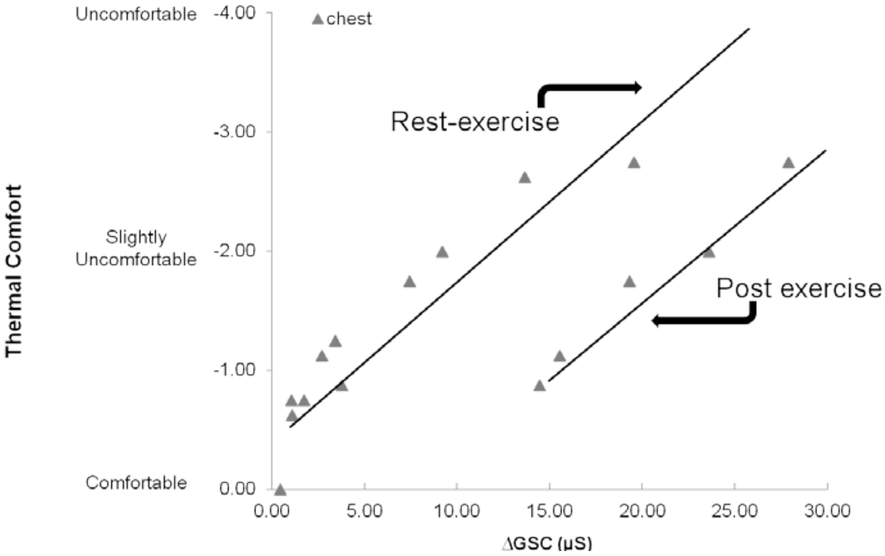


Figure 9.13: The relationship between thermal comfort and ΔGSC at the chest (females). The line to the left represent the relationship measured during rest and exercise (R1-EX3) inclusively and the line to the right represent the relationship measured from the last data point during exercise and the recovery period, labelled post exercise (EX3-PEX2).

A hysteresis effect occurs for the relationship between thermal comfort and ΔGSC, as can be seen in Figure 9.13. As recovery begins ΔGSC decreases at a much slower rate than thermal comfort and does not follow the same path on return to a comfortable state. This is illustrated in Figure 9.13, with R1-EX3 shown by the line on the left and EX3-PEX2 shown by the line that has shifted to the right. Thermal comfort for each location was plotted against each of the physiological variables for males and females and separate plots were produced for R1-EX3 and from EX3-PEX1 (Figure 9.11 and Figure 9.12). It is clear from these graphs that the relationship between the physiological variables and thermal comfort is not the same with increasing or decreasing sweating heat load. This is particularly true for ΔGSC in the male data which had a weaker relationship with thermal comfort than that of the females. This is because ΔGSC declines at a much slower rate than thermal comfort, which may be due to an inability to evaporate sweat from the contact point of the electrode. However, this was a similar response for all physiological variables, such as T_{sk}, T_c, T_b, and the various sweat measurements which declined, but not at the same rate as thermal comfort. The skin still contains sweat as noted by the HYD and ∆GSC and the temperature very slowly decreases yet thermal comfort changes quickly. The drive for thermal comfort post exercise is not fully understood and there is limited research in this area. It may be associated with the sudden change in heat production as exercise stops as it is clear that the physiological responses do not respond as quickly as thermal comfort. Further research needs to be conducted in this area, particularly as thermal comfort and the physiological measurements did not return to baseline in this study.

9.5 Conclusion

This study aimed to understand the process of sweat production and how it influenced ∆GSC during the different levels of sweat rate (low, medium, high and post exercise). The relationship between thermal comfort and the process of sweating was also investigated. The following conclusions can be drawn.

- RSR did not initially increase, yet ∆GSC and HYD did which is associated with pre-secretory sweat gland activity and sweat within the skin.
- RSR increase prior to the plateau in HYD, which suggests that the corneum does not have to be maximally hydrated for sweat to be released onto the skin as suggested by others.
- HYD has an upper limit which corresponds to the stratum corneum being maximally hydrated. Beyond this point RSR and ∆GSC continue to increase substantially.
- After the cessation of exercise, a fast reduction occurs in RSR and ∆GSC yet HYD remains elevated.
- Thermal comfort has a strong relationship with both ∆GSC and HYD.
- The strongest correlate with thermal comfort in an incremental exercise protocol when nude is HYD.
- ∆GSC is a good correlate to comfort whilst wearing clothing and up to the point where a sweat layer is present on the skin. Higher sweat rates increase ∆GSC, but have no further impact on comfort.
- The drive for thermal comfort post exercise may be associated with the sudden change in heat production when exercise stops as it is clear that the physiological responses do not respond as quickly as thermal comfort.

Chapter ten

Conclusions, Application of Research and Future Recommendations

10 Chapter Summary

This chapter will highlight the main findings from the research conducted in this thesis. The application of the research will also be discussed, along with recommendations for future research.

10.1 Thesis overview

The aim of this thesis was to investigate regional differences in various perceptual responses (thermal comfort, thermal sensation and wetness) to temperature and sweat during exercise in moderate-hot conditions. The initial study investigated the regional differences in sensitivity to a hot stimulus during rest and exercise. The study was also concerned with any gender differences. The second study investigated regional differences in sensitivity to local skin wettedness (w_{local}) on local and whole body thermal comfort and wetness sensation. It became apparent that this research needed to be progressed to conditions of high thermal discomfort and of high w_{local}. However, limitations of the measurement of w_{local} were noted, particularly of a ceiling effect during high sweat production. Therefore it was necessary to introduce an alternative physiological variable to replace or aid the prediction for thermal comfort during high metabolic rate and/or high sweat production. The chosen variable was galvanic skin conductance (GSC). From this point on, the thesis was concerned with two things, factors influencing thermal comfort and understanding the measurement of GSC.

10.2 Conclusions

The findings from this thesis are separated into four main sections, including perception of temperature, perception of thermal comfort, perception of wetness and the measurement of galvanic skin conductance.

10.2.1 Thermal sensation

In Chapter 4, thermal sensation to a hot-dry thermal stimulus (40°C thermal probe) was investigated on males and females during rest and exercise. The sensitivity to the stimulus was measured using magnitude estimation in which both transient and steady state responses were investigated. Sensation magnitude declines with time, which is associated with an overshoot response of the thermoreceptors on initial contact. Local skin temperature will affect thermal sensation during transient responses and this was accounted for; hereafter referred to as thermal sensitivity or TTS_s. Steady state responses were measured after 10 seconds which was considered long enough for initial skin temperature to not have an effect on sensation; hereafter referred to as magnitude sensation or SSTS. Although exercise only significantly reduced magnitude sensation in males and at select locations for females, trends in the data suggest that exercise also reduces thermal sensitivity. This effect is referred to as EIA (exercise induced analgesia) in which neural and hormonal changes occur as a result of exercise (Koltyn, 2000).

The findings suggest that thermal sensitivity will not differ between genders during rest or exercise. However, magnitude sensation was stronger in females than males. Additionally, regional sensitivity and magnitude sensation was similar across the body for males, but females clearly displayed several regional differences. The pattern suggested that TTS and SSTS were greatest at the head, then the torso and declined towards the extremities. This supports previous research that consistently defines the head as a sensitive area for warmth due to the large number of thermoreceptors and the importance of keeping the brain within a thermo-prescriptive zone (Strughold and Porz, 1931, cited in Parsons, p59; Nadel et al. 1973; Cabanac, 1993; Nagasaka et al., 1998). Additionally, the torso also contains vital organs which may explain why it was more sensitive than the extremities; the legs were particularly low sensitive sites in both genders. Intra-segmental differences were also noted and the torso area showed clear differences with the lateral aspect being more sensitive than the medial aspect of the front torso. However due to the methodology employed in this study it is possible that a ‘dual’ neural stimulus between mechanoreceptors and thermoreceptors of this region occurred.

Collectively the findings from Chapter 4 suggest that clothing manufacturers should consider the fact that females will be more sensitive to heat than males and they are likely to demonstrate more regional differences in their sensitivity. The focus of the designers' attention should be drawn to areas of the head and lateral torso as these are highly sensitive areas.

10.2.2 Wetness sensation

The lack of wet sensing receptors in human skin has resulted in a large amount of research into and hypotheses about how we sense wet skin. The change of T_{sk} that is brought about by evaporative cooling has been put forward as a theory of how we sense wetness (Bentley, 1990; Plante et al. 1995; Newton et al. 2009). However, in all the studies conducted in this thesis T_{sk} was either stable or increased and a perception of wetness was nevertheless apparent. Wetness sensation had a strong relationship with w_{local} and ∆GSC, but inconsistent relationships with T_{sk}. Much of the previous research claiming the involvement of T_{sk} on the perception of wetness was conducted in conditions where fluid is applied onto the skin or changes are made in the microclimate as opposed to allowing wetness to be detected through the process of sweat production (Plante et al. 1995, Bentley, 1990; Newton et al. 2009). When sweat is produced, it is transferred through the epidermis and released onto the skin surface. During this process the epidermis swells and the sensitivity of receptors increases (Kerslake, 1972; Willis, 1985, cited in Li, 2001, p.37). Different afferent inputs must be apparent in the sensation of wetness when water is either applied onto the skin or changes in the microclimate than when sweat is produced and released. In the studies conducted in this thesis both local T_{sk} and w_{local} and ∆GSC were allowed to increase simultaneously and therefore direct assumptions about what is controlling wetness sensation cannot be implied; but an important conclusion is that a drop in T_{sk} is not required.

There are no definable sense organs for thermal comfort or wetness sensation and this thesis indicates that these perceptual responses are closely linked. In some instances the body will detect moisture before it is felt uncomfortable and vice-versa but it is not clear why this occurs. What is certain is that there may be differences between the amount of moisture that causes discomfort and the sensation of wetness across regions, but once a given wetness sensation is reached the thermal comfort will be the same regardless of location.

10.2.3 Thermal comfort

The main body of research from the thesis is associated with physiological factors influencing thermal comfort. In Chapter 5 the influence of local skin wettedness (w_{local}) on local thermal comfort was investigated in a specially designed protocol where w_{local}

across the body was controlled to be either within a prescribed comfort zone (<0.30) according to Gagge et al. (1969a) or beyond it (>0.30). The study replicated the work of Fukazawa and Havenith (2009) with alterations to the methodology that should increase the contrast between zones, with the goal to determine whether the extremities are actually more sensitive than the torso and confirm local thermal comfort limits. Strong correlations existed between local thermal comfort and the respective w_{local} ($r^2>0.88$, $p<0.05$). The thermal comfort limit was defined as the w_{local} value at which participants no longer felt comfortable. Regional comfort limits for w_{local} were identified (in order of high-low sensitivity); lower back, upper legs, lower legs, abdomen, chest, upper back, upper arms and lower arms.

The findings of this study highlighted the true local thermal comfort limits of each zone without any other sites across the body having an influence on thermal comfort. However, in order to provide results with ecological validity for clothing manufacturers the natural distribution of sweat production, skin temperature and perceptual responses should be considered. Chapter 7 and 8 investigated the relationship between local thermal comfort and w_{local} during two exercise intensities that allowed physiological and perceptual responses to increase naturally. From pilot tests it was apparent that a ceiling effect in w_{local} would emerge. Having established the reliability of galvanic skin conductance as a measure of sudomotor activity in a preceding chapter (reviewed below) and confirming that it should be standardised as a change from baseline (ΔGSC) to reduce the errors in its measurement, the relationship between thermal comfort and GSC was also investigated. The main finding from this chapter is that during conditions of low sweat production, or when thermal discomfort is minimal, both ΔGSC and w_{local} can be used as a predictor of thermal comfort. However, if sweat production is high and thermal discomfort expected to be greater than ‘slightly uncomfortable’ then ΔGSC should be used as a predictor. This claim is relevant for males, but for females both ΔGSC and w_{local} can predict thermal discomfort. It is likely that the lower sweat production in females can account for this.

Several ideas are proposed to determine why ΔGSC is a better predictor of thermal comfort than w_{local}. Firstly, w_{local} was measured using humidity sensors located in the microclimate, approximately 0.2 cm from the skin. During the male trials (of Chapter 7) the skin appeared to be completely saturated, but w_{local} did not exceed 0.85 ± 0.09 and tended to show a ceiling effect >0.60. It is plausible that distance between the humidity sensor and the skin may cause an underestimation of w_{local}. Secondly, as there are no definable sense organs that influence thermal comfort it is likely to be influenced by a combined afferent neural stimulation of various receptors. These receptors are located in the epidermis and when sweat is produced, it is transferred through the epidermis and released onto the skin surface. During this process the epidermis swells and the sensitivity of receptors are said to increase (Kerslake, 1972). In Chapter 9, the influence of epidermal hydration on thermal comfort was assessed using a moisture meter that measures the hydration of the upper layers of the skin, i.e. the stratum corneum. The findings showed a strong correlation between thermal comfort and ΔGSC (r^2>0.79) and epidermal hydration (r^2>0.78). The findings suggest that ΔGSC reflects the process of sweat production more closely than w_{local} as it measures pre-secretory sweat gland activity and epidermal hydration where the receptors are located (these findings will be discussed later). The strength of the relationship between thermal comfort and epidermal hydration and ΔGSC suggest that thermal comfort is strongly influenced by sweat within the epidermis. This may explain why on numerous occasions thermal comfort had a stronger relationship with ΔGSC than w_{local}. Collectively, these findings suggest that it is not the function of sweating that cannot predict thermal comfort during high sweat rates but w_{local} as a parameter on its own.

As stated earlier the relationship between thermal comfort and w_{local} were investigated in two separate trials. In each study the thermal comfort limit (i.e. when participants no longer felt comfortable) were indentified. In Chapter 5 the true local thermal comfort limits of each zone were identified (in order of high-low sensitivity); lower back, upper legs, lower legs, abdomen, chest, upper back, upper arms and lower arms. In Chapter 7 the local thermal comfort limits were identified in conditions whereby w_{local} increased across the whole body at a natural rate without any manipulation. Comparing the w_{local} comfort limits of the two studies revealed similar comfort limits at the torso. This suggested that the torso is not much influenced by the distribution of w from other areas. However, lower comfort limits at the extremities were found in Chapter 7, where w_{local} varied naturally in comparison to the controlled conditions in Chapter 5. This is explained with a model of segmental interaction; the torso will naturally produce more sweat than the extremities at all times and the thermal comfort of areas with low w_{local} appear to be more affected by other wetter areas. It is possible that these areas will produce so much more sweat than the extremities that they dominate local thermal comfort across individual locations across the whole body.

Gender differences in thermal comfort were investigated in Chapter 7 and 8. Similarities in regional differences in the w_{local} comfort limits were noted, with the extremities being more sensitive than the torso. However, this can be explained by the above mechanisms of segmental interaction. Although the pattern was similar, the w_{local} comfort limits were lower for females than males across the body; once again indicating females are more sensitive locally and across the whole body than males; though referring to moisture his time. The maximum discomfort experienced was lower for females than males and this corresponded to a lower w_{local}, ΔGSC and GSL. This suggests that higher discomfort scores are relative to the amount of sweat produced. In this light, it may be relevant for sports clothing designers to consider thermal comfort in two forms; its onset and the degree of discomfort experienced.

The influence of clothing may be a factor to consider in future research. Most of the studies in this thesis have investigated thermal comfort on clothed participants whilst the results from this study (Chapter 9) were conducted on semi-nude participants. Further research is required to understand in which conditions these predictors are best used as the findings suggest that ΔGSC is a good predictor of comfort while wearing clothing and epidermal hydration on nude participants.

Thermal comfort post exercise was assessed in the penultimate chapter and it was evident that relationship between the physiological variables and thermal comfort is not the same with increasing or decreasing sweating heat load. All physiological responses declined at a much slower rate than thermal comfort. The skin still contains sweat as noted by the elevated hydration levels in the epidermis and ΔGSC. Skin and core temperature very slowly decreased yet thermal comfort changed much quicker. The drive for thermal comfort post exercise may be associated with the sudden change in heat production when exercise stops as it is clear that the physiological responses do not respond as quickly as thermal comfort to cessation of exercise. Further research is required to consider factors that drive thermal comfort.

10.2.4 Galvanic skin conductance

Various investigations relating to galvanic skin conductance (GSC) were carried out to determine its usability in thermophysiological research and as a predictor of thermal comfort. In several pilot tests it was established that GSC had strong correlations with various physiological response to exercise in the heat (T_c, T_b and mean T_{sk}, RSR and w_{local}). It was also established that there would be no influence of skin blood on the measurement of ΔGSC. Collectively these findings suggest that it can be used in thermoregulatory research and the measure is related to the amount of sweat produced.

As GSC is an arbitrary unit and due to the number of potential measurement errors, both systematic and unsystematic, it is important that GSC is standardised. Various methods were investigated and although standardising the values obtained relative to an individual’s minimum and maximum response, uncertainties exist over whether a maximum GSC can ever reliably be achieved. Because of this uncertainty, it was deemed appropriate to express it as a change from baseline (ΔGSC) for this thesis. With this in mind, it is imperative that a minimum GSC value is obtained to reduce any sources of error in its estimation.

Following these investigations outlined above, the relationship between thermal comfort and ΔGSC was investigated and the findings have been discussed above. The penultimate chapter of this thesis aimed to explore the measurement of ΔGSC and understand the extent to which it is influenced by pre-secretory sweat gland activity, epidermal hydration and the amount of sweat present on the skin surface. A hypothetical electrical circuit analogy model was illustrated (Chapter 9, Figure 9.3, page 201) to indicate areas which were thought to contribute to ΔGSC. These included pre-secretory sweat gland activity (labelled SD1), sweat within the dermis (labelled D1), sweat within the stratum corneum (labelled E2) and sweat on the skin surface (labelled E1). In a test where sweat production was very slowly increased towards maximum values, the contributions of each of these areas to ΔGSC were partially established. From all studies on ΔGSC in this thesis a new hypothetical electrical circuit analogy model can be drawn which is illustrated below in Figure 10.1. The figure differs predominately at E1 where it is only the sweat on the surface that is in direct contact with the electrode that influences ΔGSC. Sweat on the skin surface around the electrodes does not influence ΔGSC. These findings were also found in various pilot tests where artificial sweat was sprayed either around the electrodes or underneath the electrode contact point.

The findings suggest that ΔGSC measures pre-secretory sweat gland activity as indicated by a concomitant increase in epidermal hydration, prior to sweat being visible on the skin surface. It was found that the stratum corneum hydrates, but has an upper limit which indicates that it is close to being maximally hydrated. RSR will increase prior to the plateau in HYD, which suggests that the corneum does not have to be maximally hydrated for sweat to be released onto the skin as suggested by others. Small changes were observed in ΔGSC during pre-secretory sweat gland activity and once the epidermis was maximally hydrated ΔGSC and RSR markedly increased. These findings suggest that ΔGSC is predominately influenced by the amount of sweat on the skin surface. However, as stated earlier, the influence of surface sweat on the measurement of ΔGSC is limited to the sweat in direct contact with the electrodes and not the sweat surrounding this area (as shown in Figure 10.1).

Some factors still remain uncertain and require further investigations. This includes the influence of sweat content (sodium chloride) on GSC as conductivity measuring devices are often used to infer the sodium chloride content in sweat or the reabsorption capacity of the sweat glands (Shamsuddin et al. 2005). One other factor requiring further consideration is the measurement of ΔGSC after the cessation of exercise. RSR quickly declines post exercise, which is not mirrored by ΔGSC. This may be associated with sweat remaining within the glands and in the epidermis and the inability of sweat to evaporate from the contact point of the electrode.

10.3 Application of Research

The present research was part funded by Oxylane research; a research and design department for the French sports clothing manufacturing company Decathlon. The equations using w_{local} as a predictor of local thermal comfort (from Chapter 5, 7 and 8) have been used by Oxylane group in manikin studies. Clothing already produced by Decathlon or new prototypes are tested on thermal manikins from which it can be determined whether or not the clothing will result in local or whole body thermal comfort. This is achieved by assessing the clothing properties for their thermal resistance and vapour resistance across the whole body and numerous individual locations. This information, alongside the metabolic rate and the environmental conditions in which the clothing was tested, is put into a model that predicts local sweat production across the body and estimates the local skin wettedness values. As a result, the researchers are able to determine whether the tested clothing causes local and or whole body discomfort and they can make changes to the clothing accordingly. This may vary from ventilation openings to the use of different materials. The regional variations in sensitivity to the build up of sweat (as measured by w_{local} and/or ΔGSC) have been interpreted by Oxylane research to design sports clothing in terms of required ventilation and material properties that optimise thermoregulation and consumer thermal comfort. Based on the findings of Chapters 5, 7 and 8 it is proposed to the clothing designers that although the extremities appear to be more sensitive than the torso, the clothing should facilitate the evaporation of sweat from the torso as this area will dominate local discomfort across the whole body.

Currently, Oxylane group can only use the information of regional sensitivity based on w_{local} data. Further research is required to enable them to interpret and utilise ΔGSC with thermal manikin data as it is shown to be a stronger predictor of thermal comfort at higher sweating levels in comparison to w_{local}.

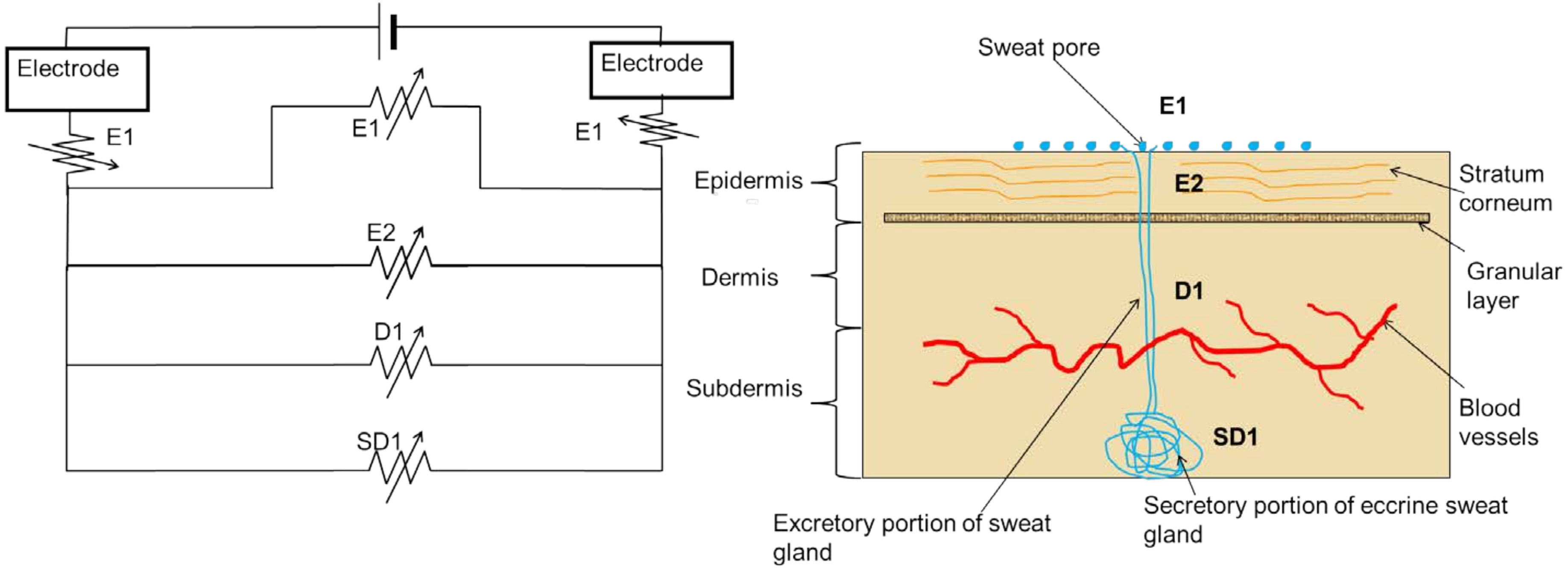


Figure 10.1: An updated version of a hypothetical electrical circuit analogy model (left). The labelled resistances correspond to the areas within the skin (diagram on the right) which contribute towards the resistance/conductance of the skin. Label E1 indicates the effect of sweat on the skin surface directly underneath electrode; E2 indicates the effect of hydration of the stratum corneum; D1 indicates sweat travelling through the duct within the skin; SD1 indicates sweat being produced within the gland

10.4 Recommendations for future research

This thesis has investigated various physiological factors that influence perceptual responses during rest and exercise in various conditions. Recommendations for different research are proposed.

10.4.1 Thermal comfort

- The influence of clothing on thermal comfort was raised in Chapter 9 as the findings on semi-nude participants were different to previous chapters on clothed participants. Clothing absorbs moisture and heat from the body and during exercise the material regularly comes into contact with the skin and thus stimulates a variety of mechanical receptors. The skin-fabric interaction may influence thermal comfort during exercise in the heat.

- The current research was only tested on Caucasian participants aged between 18 and 45 years. Comparison of local sensitivity with different ethnic groups and across different ages would be of interests, particularly as thermoregulatory function varies across such populations.

- Chapter 9 was the only study whereby thermal comfort post exercise was investigated. It was clear from the results that thermal comfort improved at a faster rate than any physiological responses measured. Further research is required to understand the drive for thermal comfort post exercise.

- The true local thermal comfort limits to w_{local} were indentified in males (Chapter 5). In the proceeding chapter, the natural increase of the physiological and perceptual response during exercise was investigated in males and females. These chapters provided a global picture of how local regions interact and influence local thermal comfort across the body. It would be of interest to repeat the trials of Chapter 5 on females to identify the true local thermal comfort limits to w_{local}.

10.4.2 Wetness sensation

- The perception of wetness is typically claimed to be influenced by the movement of sweat across the skin surface or by a drop in skin temperature. However, in several chapters of this thesis T_{sk} increased or was stable alongside an increase in wetness sensation. The movement of sweat along the skin surface was not directly measured although participants could rate ‘dripping wet’ on the sensation scale. Further research is still required to determine what influences wetness sensation as both local T_{sk} and w_{local} and ΔGSC were allowed to increase simultaneously in the present research and thus direct assumptions about which of these is controlling wetness sensation cannot be implied.

- The difference between the influence of loose fitting clothing and tight fitting clothing is of interest, particularly on the perception of wetness. When wearing loose fitting clothing, as used in this thesis, the movement of sweat across the skin is easily detected by participants. However, wearing tight fitting clothing causes sweat to be absorbed by the clothing and prevents movement of sweat across the skin.

10.4.3 Measuring galvanic skin conductance

- As GSC is an arbitrary measurement, standardising in a similar way to that done for measuring skin blood flow needs to be established. Some techniques were investigated in this thesis (artificial spraying and exposure and exercise in hot conditions) yet uncertainties exist over whether maximal sweat production has been reached. Other possible techniques which require thought include stimulating the sweat glands with cholinergic agonists (pilocarpine, acetylcholine or methacholine) via intradermal injections.
- GSC may be influenced by the concentration of Sodium Chloride (NaCl) in sweat, but to what extent this is influenced by the concentration of sweat on the skin or within it remains uncertain and requires investigating.

References

Abenoza, P. & Ackerman, A.B. (1990). *Neoplasms with Eccrine Differentiation.* Philadelphia: Lea & Febiger, 44–72.

Agache, P. & Humbert, P. (2004). *Measuring the Skin*. Springer-Verlag, Berlin, Germany.

Alanen, E., Nuutinen, J., Nichlén, K., Lahtinen, T & Mönkkönen, J. (2004). Measurement of hydration in the stratum corneum with the MoistureMeter and comparison with the Corneometer. *Skin, Research and Technology*, 10, 1, 32-37.

Albaum, G. (1997). The Likert Scale revisited: An alternative version. *The Journal of the Market Research Society*, 39, 2, 331-348.

American College of Sport Medicine. (2005). *ACSM's guidelines for exercise testing and prescription.* 7th ed. Lippincott Williams & Wilkins.

Arens, E.A. & Zhang, H., (2006). The skin's role in human thermoregulation and comfort. In: Pan, N. and Gibson, P. (eds.) *Thermal and moisture transport in Fibrous Materials.* USA: Woodhead Publishing Ltd, pp. 560.

Arens, E.A., Zhang, K. & Huizenga, C., (2005a). Partial- and whole body thermal sensations and comfort: Part II: Non-uniform environmental conditions. Journal of Thermal Biology, 31, 60-66.

ARENS, E.A., ZHANG, K. & HUIZENGA, C. (2005b). Partial and whole body thermal sensations and comfort; Part I: Uniform environmental conditions. Journal of Thermal Biology31, 53-59.

Armel, K.C. & Ramachandran, V.S. (2003). Projecting sensations to external objects: evidence from skin conductance response. *Proceedings of the Royal Society of London.Series B: Biological Sciences,* 270(1523), 1499.

ASHRAE, (1997). *Thermal comfort. ASHRAE handbook of fundamentals.* Atlanta, USA

Attia, M. & Engel, P. (1982). Thermal pleasantness sensation: an indicator of thermal stress. *European Journal of Applied Physiology and Occupational Physiology*, 50, 1, 55–70.

Avellini. B.A. & Kamon, E. (1980). Physiological responses of physically fit men and women to acclimatization to humid heat. *Journal of Applied Physiology*, 49, 24-261.

Beaumont, A. & Hughes, J. (1979). Biology of opioid peptides. *Annual Review of Pharmacology and Toxicology,* 19, 1, 245-267.

Bedford, T. (1936). *The warmth factor in comfrt at work: A Physiological study of heating and ventilation.* 76. London: Industrial Health Research Board Report.

Bentley, I.M. (1990). The synthetic experiment. *Amerian Journal of Psychology,* 11, 405-425.

Benzinger, T.H. (1963). Peripheral cold- and central warm-reception, main origins of human thermal discomfort. *Proceedings of the National Academy of Sciences of the United States of America,* 49, 832-839.

Berglund, L.G. (1995). Comfort criteria - humidity and standards, *Proceedings of the Pan Pacific symposium on Buildings and Urban Environmental Conditioning in Asia*, March 16-18 1995, 369.

Berglund, L.G. & Cunningham, D.J. (1986). *Parameters of Human Discomfort in Warm environments.* 92. ASHRAE Transcations.

Berglund, L.G., Oohori, T., Cunningham, D.J. & Gagge, A.P. (1985). Vapour resistance of clothing, local skin wettedness and discomfort. *ASHRAE Transcation,* 91, 3-12.

Bircher, A., Boer, E.M., Agner, T., Wahlberg, J.E. & Serup, J. (1994). Guidelines for measurement of cutaneous blood flow by laser Doppler flowmetry. *Contact Dermatitis,* 30, 2, 65-72.

Bittel, J. & Henane, R. (1975). Comparison of thermal exchanges in men and women under neutral and hot conditions. *The Journal of Physiology,* 250, 3, 475-489.

Boucsein, W. (2011). *Electrodermal activity.* 2nd ed. New York, USA: Springer.

Brake, D. & Bates, G. (2003). Fluid losses and hydration status of industrial workers under thermal stress working extended shifts. *Occupational and Environmental Medicine,* 60, 2, 90-96.

Branton, P. (1969). Behaviour, body mechanics and discomfort. *Ergonomics,* 12, 2, 316-327.

Bullock, J. & Boyle, J & Wang, M.B. (2001). *Physiology.* 4th ed. Lippincott Williams & Wilkins.

Cabanac, M.(1969). Plaisir ou deplaisir de la sensation thermique et homeothermie. *Physiology and Behaviour*. 4, 3, 359–364.

Cabanac, M. (1993). Selective brain cooling in humans:" fancy" or fact? *The FASEB journal,* 7, 12, 1143-1146.

Caldwell, J.N., Nykvist, A., Powers, N., Notley, S., Lee, D. and Peoples, G. & Taylor, N. (2011). An Investigation of forearm vasomotor and suomotor thresholds during passive heating, following whole body cooling. *XIV International Conferences of Environmental Ergonomics*, Nafpilo, Greece, 10-15 July, Paschalidis Medical Publisher.

Candas, V., Libert, J. and Vogt, J. (1980). Effect of hidromeiosis on sweat drippage during acclimation to humid heat. *European Journal of Applied Physiology and Occupational Physiology,* 44, 2, 123-133.

Candas, V., Libert, J.P. & Vogt, J.J., (1979a). Human skin wettedness and evaporative efficiency of sweating. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology,* 46, 3, 522-528.

CANDAS, V., LIBERT, J.P. & VOGT, J.J. (1979b). Influence of air velocity and heat acclimation on human skin wettedness and sweating efficiency. *Journal of Applied Physiology,* 47(6), pp. 1194-1200.

Chatonnet. J. & Cabanac, M. (1965). The perception of thermal comfort. *International Journal of Biometeorology*, 9, 2, 183-193.

Chen, C., Essick, G., Kelly, D., Young, M., Nestor, J. & Masse, B. (1995). Gender-, side-and site-dependent variations in human perioral spatial resolution. *Archives of Oral Biology,* 40, 6, 539-548.

Clark, R., Mullan, B. & Pugh, L. (1977). Skin temperature during running--a study using infra-red colour thermography. *The Journal of Physiology,* 267, 1, 53-62.

Claus, D., Hilz, M.J., Hummer, L. & Neundörfer, B. (1987). Methods of measurement of thermal thresholds. *Acta Neurologica Scandinavica*. 76, 4, 288–296.

Cotter, J., Zeyl, A., Keizer, E. & Taylor, N. (1996). The role of local skin temperature in determining the perception of local and whole-body thermal state. In: Shapiro Y. M., Epstein D. S., Jerusalem Y. (eds.) *Environmental Ergonomics Recent Progress and New Frontiers*. Tel Aviv, Israel: Freund Publishing House Ltd. pp. 85–88

Cotter, J.D. & Taylor, N.A. (2005). The distribution of cutaneous sudomotor and alliesthesial thermosensitivity in mildly heat-stressed humans: an open-loop approach. *The Journal of Physiology,* 565, 1, 335-345.

Cotter, J.D., Patterson, M.J. & Taylor, N.A.S., 1995. The topography of eccrine sweating in humans during exercise. *European Journal of Applied Physiology,* 71, 6, 549-554.

Cracowski, J.L., Minson, C.T., Salvat-melis, M. & Halliwill, J.R. (2006). Methodological issues in the assessment of skin microvascular endothelial function in humans. *Trends in Pharmacological Sciences,* 27(9), pp. 503-508.

Cunningham, D.J., Stolwijk, J. & Wenger, C. (1978). Comparative thermoregulatory responses of resting men and women. *Journal of Applied Physiology,* 45, 6, 908-915.

Darrow, C.W. (1964). The rationale for treating the change in galvanic skin response as a change in conductance. *Psychophysiology,* 1, 1, 31-38.

Davey, S., Reily, T. & Newton, M & Tipton, M. (2007). The reproducability and validity of visual analogue scales (VAS) that assess thermal perceptions in stable and dynamic, asymmetric environments, *Environmental Ergonomics XII. Proceedings of the 12th International Conference on Enviornmental Ergonomics*, 2007, August 19-24 2007, Environmental Ergonomics, pp. 114-116.

Davies, C.T.M. (1979). Thermoregulation during exercise in relation to sex and age. *European Journal of Applied Physiology and Occupational Physiology,* 42, 2, 71-79.

Doherty, T. & Arens, E.A. (1988). Evaluation of the Physiological Bases of Thermal Comfort Models. *Indoor Environmental Quality*, Centre for the built Environment, UC Berkley.

Edelberg, R. (1967). Electrical properties of skin. In: C.C. BROWN, ed, *Methods in Psychophysiology.* Baltimore, USA.: Williams & Wilkins, pp. 1-53.

Edelberg, R. (1972). Electrical activity of the skin: Its measurements and uses in psychophysiology. In: Greenfield, N.S. & Sternbach, R.A. (eds.) *Handbook of Psychophysiology.* New York, USA: Holt, Rinchart & Winston, pp. 367-418.

Epstein, Y., Stroschein, L. & Pandolf, K. (1987). Predicting metabolic cost of running with and without backpack loads. *European Journal of Applied Physiology and Occupational Physiology,* 56, 5, 495-500.

Fanger, P.O. (1970). *Thermal Comfort.* Copenhagen, Denmark: Danish Technical Press.

Fillingim, R.B., Maixner, W., Kincaid, S. & Silva, S. (1998). Sex differences in temporal summation but not sensory-discriminative processing of thermal pain. *Pain,* 75, 1, 121-127.

Fluhr, J.W., Gloor, M., Lazzerini, S., Kleesz, P., Grieshaber R. and Berardesca, E. (1999). Comparative study of five instruments measuring stratum corneurn hydration (Comeometer CM 820 and CM 825, Skicon 200, Nova DPM 9003, DermaLab). Part I. *In vitro. Skin Research and Technology*, 5, pp. 161-170

Fowler, C.J., Carroll, M., Burns, D., Howe, N. & Robinson, K. (1987). A portable system for measuring cutaneous thresholds for warming and cooling. *Journal of Neurology, Neurosurgery & Psychiatry,* 50, 9, 1211-1215.

Fowles, D.C. (1986). The eccrine system and electrodermal activity. In: M.G.H. COLES, E. DONCHIN and S.W. PORGES, eds, *Psychophysiology.* New York, USA: Guilford Press, 51-96.

Fox, R., Lofstedt, B., Woodward, P.M., Eriksson, E. and Werkstrom, B. (1969). Comparison of thermoregulatory function in men and women. *Journal of Applied Physiology,* 26, 4, 444-453.

Frye, A.J. & Kamon, E. (1981). Responses to dry heat of men and women with similar aerobic capacities. *Journal of Applied Physiology*, 50, 65-70.

Fukazawa, T. & Havenith, G. (2009). Differences in comfort perception in relation to local and whole body skin wettedness. *European Journal of Applied Physiology, 106, 1, 15-24*.

Gagge, A.P. (1937). A new physiological variable associated with sensible and insensible perspiration. *American Journal of Physiology,* 120, 2, 277-287.

Gagge, A.P. (1936). The linearity criterion as applied to partitional calorimetry. *American Journal of Physiology,* 116, 3, 656-668.

Gagge, A.P., Stolwijk, J.A.J. & Hardy, J.D. (1967). Comfort and thermal sensations and associated physiological responses at various ambient temperatures. *Environmental Research,* 1, 1, 1-20.

Gagge, A.P., Stolwijk, J.A. & Nishi, T. (1969a). The prediction of thermal comfort when thermal equilibrium is maintained by sweating. *ASHRAE Transactions,* 75, 2, 108-121.

Gagge, A.P., Stolwijk, J.A. & Saltin, B. (1969b). Comfort and thermal sensations and associated physiological responses during exercise at various ambient temperatures. *Environmental Research,* 2, 3, 209-229.

Geddes, L. (2002). The truth shall set you free [development of the polygraph]. *Engineering in Medicine and Biology Magazine, IEEE,* 21, 3, 97-100.

Gibson, L.E. & San'Agnese, P.A. (1963). Studies of salt excertion in sweat:Relationship between rate, conductivity and electroylte compsoition of sweat from patients with cystic fibrosis and from contol subjects. *The Journal of Pediatrics*, 62, 6, 85-867.

Givoni, B. (1976). *Man, climate and Architecture.* 2nd edition. UK: Applied Science Publishers.

Golja, P., Tipton, M.J. and Mekjavic, I.B. (2003). Cutaneous thermal thresholds--the reproducibility of their measurements and the effect of gender. *Journal of Thermal Biology,* 28, 4, 341-346.

Griffiths, I.D. and Boyce, P.R. (1971). Performance and Thermal Comfort. *Ergonomics,* 14, 4, 457-468.

Grimnes, S. (1982). Psychogalvanic reflex and changes in electrical parameters of dry skin. *Medical and Biological Engineering and Computing,* 20, 6, 734-740.

Guieu, R., Blin, O., Pouget, J. & Serratrice, G. (1992). Nociceptive threshold and physical activity. *The Canadian Journal of Neurological Sciences .Le Journal Canadien des Sciences Neurologiques,* 19, 1, 69-71.

Guyton, A.C. (1991). *Textbook of Medical Physiology.* Philadelphia, USA.: W.B. Saunders.

Gwosdow, A.R., Nielsen, R., Berglund, L.G., Dubois, A.B. & Tremml, P.G. (1989). Effect of thermal conditions on the acceptability of respiratory protective devices on humans at rest. *American Industrial Hygiene Association Journal,* 50, 4, 188-195.

Ha, M., Yamashita, Y. & Tokura, H. (1995). Effects of moisture absorption by clothing on thermal responses during intermittent exercise at 24 degrees C. *European Journal of Applied Physiology and Occupational Physiology,* 71, 2-3, 266-271.

Hansson, P., Backonja, M. & Bouhassira, D. (2007). Usefulness and limitations of quantitative sensory testing: clinical and research application in neuropathic pain states. *Pain-Journal of the International Association for the Study of Pain,* 129, 3, 256-259.

Hardy, J.D. & Dubois, E.F. (1938). Basal metabolism, radiation, convection and evaporation at temperatures from 22°C to 35°C. *Journal of Nutrition*, 15, 477-492.

Hardy, J.D, Gagge, A.P. and Stolwijk, J.A.J. (1970). *Physiological and Behavioural Temperature Regulation.*Springfield, IL, Chas, C.Thomas.

Havenith, G., Fogarty, A., Bartlett, R., Smith, C. & Ventenat, V. (2008). Male and female upper body sweat distribution during running measured with technical absorbents. *European Journal of Applied Physiology,* 104, 2, 245-255.

Havenith, G., Holmér, I. & Parsons, K. (2002). Personal factors in thermal comfort assessment: clothing properties and metabolic heat production. *Energy and Buildings,* 34, 6, 581-591.

Havenith, G. & van Middendorp, H. (1990). The relative influence of physical fitness, acclimatization state, anthropometric measures and gender on individual reactions to heat stress. *European Journal of Applied Physiology and Occupational Physiology,* 61, 5, 419-427.

Hertzman, A.B. (1957). Individual differences in regional sweating. *Journal of Applied Physiology,* 10, 2, 242-248.

Heyward, V.H. & Wagner, V.R. (2004). *Body composition assessment.* 2nd edn. Champaign, IL, USA: Human Kinetics.

Hoffman, R.G. & Pozos, R.S (1989). Experimental hypothermia and cold perception. *Aviation, Space, and Environmental Medicine,* 60(10 Pt 1), 964-969.

Hollies, N.R.S., Custer, A.G., Morin, C.J. & Howard, M.E. (1979). A Human Perception Analysis Approach to Clothing Comfort. *Textile Research Journal,* 49, 10, 557-564.

Inoue, Y., Tanaka, Y., Omori, K., Kuwahara, T., Ogura, Y. & Ueda, H. (2005). Sex-and menstrual cycle-related differences in sweating and cutaneous blood flow in response to passive heat exposure. *European Journal of Applied Physiology,* 94, 3, 323-332.

ISO 7730 (1995). Moderate thermal environments. Determination of the PMV and PPD indices and specification of the condition for thermal comfort. *ISO*, Geneva.

ISO 7933 (2004). Ergonomics of the thermal environment. Analytical determination and intreprtation of heat stress using calculations of the predicted heat strain. *ISO*, Geneva.

Jackson, A.S. & Pollock, M.L. (1978). Generalized equations for predicting body density of men. *British Journal of Nutrition,* 40, 3, 497-504.

Jackson, A.S., Pollock, M.L. & Ward, A. (1980). Generalized equations for predicting body density of women. *Medicine and Science in Sports and Exercise,* 12, 3, 175-182.

Jasper, H. & Penfield, W. (1954). *Epilepsy and the Functinal Anatomy of the Human Brain.* 2nd edn. Little, Brown and Co.

Johnson, L.C. & Landon, M.M. (1965). Eccrine sweat gland activity and racial differences in resting skin conductance. *Psychophysiology,* 1, 4, 322-329.

Johnson, J.M., Taylor, W.F., Shepherd, A.P. & Park, M.K. (1984). Laser-Doppler measurement of skin blood flow: comparison with plethysmography. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology,* 56, 3, 798-803.

Kemppainen, P., Pertovaara, A., Huopaniemi, T. & Johansson, G. (1986). Elevation of dental pain threshold induced in man by physical exercise is not reversed by cyproheptadine-mediated suppression of growth hormone release. *Neuroscience letters,* 70, 3, 388-392.

Kemppainen, P., Pertovaara, A., Huopaniemi, T., Johansson, G. & Karonen, S.L. (1985). Modification of dental pain and cutaneous thermal sensitivity by physical exercise in man. *Brain research,* 360, 1-2, 33-40.

Kenny, G.P., Chen, A.A., Johnston, C.E., Thoden, J.S. & Giesbrecht, G.G. (1997). Intense exercise increases the post-exercise threshold for sweating. *European journal of applied physiology,* 76, 2, 116-121.

Kenshalo SR, D.R. (1986). Somesthetic sensitivity in young and elderly humans. *Journal of Gerontology,* 41, 6, 732-742.

Kerslake D, M. (1970). Maximum sweatin at rest. In: Hardy, J.D., Gagge A.P. and Stolwijk, J.A.J. (eds.) *Physiological and Behavioural Temperature Regulation.* II edn. Springfield, IL: Thomas, pp. 139-151.

Kerslake, D.M. (1972). *The stress if hot environment.* Cambridge: Cambridge University Press.

Kilgman, A.M. (1964). The biology of the Stratum Corneum. In: Montagna, W. & Lobitz, W.C, JR. (eds.) *The epidermis.* New York, USA: Academic Press,

Koltyn, K.F. (2000). Analgesia following exercise: a review. *Sports Medicine,* 29, 2, 85-98.

Kondo, N., Shibasaki, M., Koga, S., Inoue, Y. & Crandall, C.G. (2001). Function of human eccrine sweat glads during dynamic exercise and passive heat stress. *Journal of Applied Physiology*, 90, 5, 1877-11.

Kuno, S. (1995). *Comfort and Pleasantness.* Nagoya, Japan: Pan-Pacific Symposium on Building and Urban Environmental Conditioning in Asia, 16-18 March, 383-392.

Kuno, Y. (1956). Chemistry of sweat. *Human perspiration.* Springfield, IL, Charles C Thomas Publishers, p 222-250.

Lautenbacher, S. & Strian, F. (1991). Sex differences in pain and thermal sensitivity: the role of body size. *Attention, Perception, & Psychophysics,* 50, 2, 179-183.

Lee, J.Y. and Choi, J.W., 2009. Estimation of regional body surface area covered by clothing. *人間-生活環境系学会英文誌,* 12, 1, 35-45.

Lee, J.Y., Nakao, K. & Tochihara, Y. (2011). Validity of perceived skin wettedness mapping to evaluate heat strain. *European Journal of Applied Physiology,* 111, 10, 2581-2591.

Lee, J.Y., Stone, E.A., Wakabayashi, H. & Tochihara, Y. (2009). Issues in combining the categorical and visual analog scale for the assessment of perceived thermal sensation: Methodological and conceptual considerations. *Applied Ergonomics,* 41, 2, 282-290.

Lee, U. & Tamura, T. (1995). Distribution of cold sensitivity over human skin. *Japan Society of Home Economics,* 46, 11, 1081.

Leon, G.R., Koscheyev, V.S. & Stone, E.A. (2008). Visual analog scales for assessment of thermal perception in different environments. *Aviation, Space, and Environmental Medicine,* 79, 8, 784-786.

Li, Y. (2001). *The Science of Clothing Comfort: A criticial appreciation of recent developments by Y.Li.* Oxford, UK: The Textile Institute.

Li, Y. (2005). Perceptions of temperature, moisture and comfort in clothing during environmental transients. *Ergonomics,* 48, 3, 234-248.

Li, Y., Plante, A.M., & Holcombe, B.V. (1995). Fiber Hygroscopicity and Perceptions of Dampness: Part II: Physical Mechanisms. *Textile Research Journal,* 65, 6, 316-324.

Lykken, D., Rose, R., Luther, B. & Maley, M. (1966). Correcting psychophysiological measures for individual differences in range. *Psychological Bulletin,* 66, 6, 481-484.

Lykken, D.T. & Venables, P.H. (1971). Direct measurement of skin conductance: A proposal for standardization. *Psychophysiology,* 8, 5, 656-672.

Machado-Moreira, C.A., Edkins, E., Iabushita, A.S., Maruca, P. & Taylor, N.A.S. (2009). Sweat gland recuitment following thermal and psychological stimuli. *X111 International Conference of Environmental Ergonomics*, Boston, USA, 2-7 August. Available from: http://www.environmental-ergonomics.org/. [Accessed 17 June 2011].

Machado-Moreira, C.A., Smith, F., Van den Heuvel, A.,Mekjavic, I. & Taylor, N. (2008). Sweat secretion from the torso during passively-induced and exercise-related hyperthermia. *European Journal of Applied Physiology,* 104, 2, 265-270.

Machado-Moreira, C.A., Caldwell, J.N., Mekjavic, I.B. & Taylor, N.A.S. (2008). Sweat Secretion from Palmar and Dorsal Surfaces of the Hands During Passive and Active Heating. *Aviation, Space, and Environmental Medicine,* 79, 7, 1034-1040.

Marks, L.E. & Gonzalez, R.R. (1977). Thermal sensation:perceived intensity and pleasantness related to skin temperature. *Proceedings International Union of Physiology Sciences, Paris,* 13, 480.

Meh, D. & Deniˇslicˇ, M. (1994) .Quantitative assessment of thermal and pain sensitivity. Journal of Neuroloical Sciences.127, 2,164–169.

Mccook, R., Wurster, R. & Randall, W. (1965). Sudomotor and vasomotor responses to changing environmental temperature. *Journal of Applied Physiology,* 20, 3, 371-378.

Mcintyre, D.A. (1978). *Three approaches to thermal comfort.* 84. ASHRAE transactions.

Mcintyre, D.A. (1980). *Indoor Climate.* London: Applied Science Publishers.

Mckemy, D.D., Neuhausser, W.M. & Julius, D. (2002). Identification of a cold receptor reveals a general role for TRP channels in thermosensation. *Nature,* 416, 6876, 52-58.

McLellan, T.M. (1998). Sex-related differences in thermoregulatory responses while wearing protective clothing. *European Journal of Applied Physiology*, 78, 1, 28-37.

Mcnall, J., P.E., Jaxx, J., Rohles, F.H. & Nevins, R.G. & Springer, W. (1967). *Thermal comfort (thermally neutral) conditions for three levels of activity.* 73. ASHRAE.

Miller, G.A. (1956). The magical number seven, plus or minus two: some limits on our capacity for processing information. *Psychological review,* 63, 2, 81-97.

Moan, D.S., Shapio, Y., Laor, A., Izraeli, S. & Pandolf, K.B. (1999). Can gender differcnes during exercise-heat stress be assesed by the physiological strain index? *American Journal of Physiology, Regulatory Integrative and Comaprble Physiology*, 45; R1798-R1804.

Mower, G.D. (1976). Perceived intensity of peripheral thermal stimuli is indepen- dent of internal body temperature.Journal of Comparative and Physiological Psychology, 90, 12, 1152–1155.

Nadel, E.R., Bullard, R.W. & Stolwijk, J.A. (1971). Importance of skin temperature in the regulation of sweating. *Journal of Applied Physiology,* 31, 1, 80-87.

Nadel, E.R., Mitchell, J.W. & Stolwijk, J.A.J. (1973). Differential thermal sensitivity in the human skin. *PflÃ¼gers Archiv European Journal of Physiology,* 340, 1, 71-76.

Nadel, E.R. & Stolwijk, J.A. (1973). Effect of skin wettedness on sweat gland response. *Journal of Applied Physiology,* 35, 5, 689-694.

Nagasaka, T., Brinnel, H., Hales, J. & Ogawa, T. (1998). Selective brain cooling in hyperthermia: the mechanisms and medical implications. *Medical hypotheses,* 50, 3, 203-211.

Nakamura, M., Yoda, T., Crawshaw, L.I., Yasuhara, S., Saito, Y.,Kasuga, M., Nagashima, K. & Kanosue, K. (2008). Regional differences in temperature sensation and thermal comfort in humans. *Journal of Applied Physiology,* 105, 6, 1897-1906.

Newton, M., Barwood, M.J. & Tipton, M. (2009). The sensitivity of initial thermal perceptions when altering local skin temperatures by modifying microclimate relative humidity, *X111 International Conference of Environmental Ergonomics*, Boston, USA, 2-7 August. Available from: http://www.environmental-ergonomics.org/. [Accessed 17 June 2011].

Newton, M., Reilly, T., Davey, S. & Tipton, M.J. (2007). Senstivity of responses using perception scales that assess torso and overal thermal perceptions in warm stable and dynamic asymmetric environments, *X11 International Conference of Environmental Ergonomics*, Piran, Slovenia, 19-24 August.

Nicol, F., Humphreys, M., Roafs, S & Sykes, O. (1995). *Standards for Thermal Comfort.* London: Chapman & Hall.

Nielsen, R. & Endrusick, T.L. (1990). Sensations of temperature and humidity during alternative work/rest and the influence of underwear knit structure. *Ergonomics,* 33, 2, 221-234.

Nishi, Y. & Gagge, A.P. (1977). Effective temperature scale useful for hypo- and hyperbaric environments. *Aviation, Space, and Environmental Medicine,* 48, 2, 97-107.

Otto, M.W. & Dougher, M.J. (1985). Sex differences and personality factors in responsivity to pain. *Perceptual and motor skills,* 61, 2, 383-390.

Ouzzahra, Y., Havenith, G. & Redortier, B. (2012). Regional distribution of thermal senstivity to cold at rest and during mild exercise in males. *Journal of Thermal Biology*, 37, 517-523.

Paalasmaa, P., Kemppainen, P. & Pertovaara, A. (1991). Modulation of skin sensitivity by dynamic and isometric exercise in man. *European Journal of Applied Physiology and Occupational Physiology,* 62, 4, 279-285.

Pandolf, K.B., Givoni, B. & Goldman, R.F. (1977). Predicting energy expenditure whilst standing or walking with heavy loads. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology,* 43, 4, 577-581.

Parsons, K.C. (2003). *Man and his thermal environment: the effects of hot, moderate, and cold environments on human health, comfort, and performance.* 2nd edn. London, UK: Taylor & Francis.

Patterson, M.J., Galloway, S.D.R. & Nimmo, M.A. (2001). Variations in regional sweat composition in normal human males. *Experimental Physiology,* 85, 6, 869-875.

Peier, A.M., Moqrich, A., Hergarden, A.C., Reeve, A.J., Andersson, D.A., Story, G.M., Earley, T.J., Dragoni, I., Mcintyre, P., Bevan, S. & Patapoutian, A. (2002). A TRP Channel that Senses Cold Stimuli and Menthol. *Cell,* 108, 5, 705-715.

Pellerin, N. & Candas, V. (2005). Psychophysiological approach to thermal discomfort in non-uniform environments. *Elsevier Ergonomics Book Series,* 3, 251-256.

Pertovaara, A., Huopaniemi, T., Virtanen, A. & Johansson, G. (1984). The influence of exercise on dental pain thresholds and the release of stress hormones. *Physiology & Behavior,* 33, 6, 923-926.

Plante, A.M., Holcombe, B.V. & Stephens, L.G. (1995). Fiber Hygroscopicity and Perceptions of Dampness: Part I: Subjective Trials. *Textile Research Journal,* 65, 5, 293-298.

Ramanathan, N.L. (1964). A new weighting system for mean surface temperature of the human body. Journal of Applied Physiology, 19, 3, 531.

Refinetti, R. (1989). Magnitude estimation of warmth: Intra-and intersubject variability. *Attention, Perception, & Psychophysics,* 46, 1, 81-84.

Rose, R. (1964). *Preliminary studies of indicants of arousal: Measurements, inter relations and clinical correlates.* PhD Thesis. University of Minnesota: University of Minnesota.

Ross, H.E. & Murray, D.J (1996). eds, *E.H. Weber on the tactile senses.* 2nd edn. UK: Taylor and Francis.

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

Sato, K., Kang, W., Saga, K. & Sato, K. (1989a). Biology of sweat glands and their disorders. I. Normal sweat gland function. *Journal of the American Academy of Dermatology,* 20, 4, 537-563.

Sato, K., Kang, W., Saga, K. & Sato, K. (1989b). Biology of sweat glands and their disorders. II. Disorders of sweat gland function. *Journal of the American Academy of Dermatology,* 20, 5, 713-726.

Sato, K. & Sato, F. (1983). Individual variations in structure and function of human eccrine sweat gland. *The American Journal of Physiology,* 245, 2, R203-8.

Shamsuddin, A. & Togawa, T. (1998). Continuous monitoring of sweating by electrical conductivity measurement. *Physiological Measurement,* 19, 375-382.

Shibasaki, M., Wilson, T.E. & Crandall, C.G. (2006). Neural control and mechanisms of eccrine sweating during heat stress and exercise. *Journal of Applied Physiology,* 100, 5, 1692-1701.

Smith, C.J. & Havenith, G. (2011). Body mapping of sweating patterns in male athletes in mild exercise-induced hyperthermia. *European Journal of Applied Physiology,* 111, 7, 1391-1401.

Smith, C.J. & Havenith, G. (2012). Body mapping of sweating patterns in athletes: Asex comparison. Medicine and Science in Spot and Exercise, Online First 2012; doi: 10.1249/MSS.0b013e318267b0c4

Ständer, S. & Luger, T.A. (2009). Neuroreceptors & Mediators. In: Granstein, R.D. & Luger, T., ed, *Neuroimmunology of the Skin*. Berlin: Springer-Verlag, 13-23.

Stevens, J.C., Okulicz, W.C. & Marks, L.E. (1973). Temporal summation at the warmth threshold. *Attention, Perception, & Psychophysics*, 14, 2, 307-312.

Stevens, S.S. (1966). Matching functions between loudness and ten other continua. *Attention, Perception, & Psychophysics*, 1, 1, 5-8.

Stevens, J.C., Marks, L.E. & Simonson, D.C. (1974). Regional sensitivity and spatial summation in the warmth sense. *Physiology & Behavior*, 13, 6, 825-836.

Storaas, G. & Bakkevig, M.K. (1996). Correlation between measured skin wettedness and subjective sensations of skin wetness. In: The VII International Conference of Environmental Ergonomics.Jerusalem, Israel, Freund Publishing House, Ltd, pp. 131.

Szabo, G. (1962). *Advances in Biology of Skin*. New York: Pergamon.

Tan, C., Chen, W., Delbressine, F. & Rauterberg, M. (2008). Objectifying discomfort seat measurement for next generation truck driver's seat. International Federation of Automotive Engineering Societies.Student paper, (F2008-SC), 028.

Thoden, J., Kenny, G., Reardon, F., Jetfe, M. and Livingstone, S. (1994). Disturbance of thermal homeostasis during post-exercise hyperthermia. European Journal of Applied Physiology, 68, 2, 170-176.

Thomas, P.E. and Korr, I.M. (1957). Relationship between sweat gland activity and electrical resistance of the skin. *Journal of Applied Physiology,* 10, 3, 505-510.

Tiest, W.M.B.; Kosters, N.D., Kappers, A.M.L. & Daanen, H.A.M. (2012). Phase change material and the perception of wetness. *Ergonomics*, 55, 4, 508-12.

Toftum, J., Jørgensen, A.S. and Fanger, P.O. (1998). Upper limits for indoor air humidity to avoid uncomfortably humid skin. *Energy and Buildings,* 28, 1, 1-13.

Tortora, G.J. and Derrickson, B. (2006). *Principles of Anatomy and Physiology.* 11th edn. USA: John Wiley & Sons, Inc.

Umbach, K.H. (1982). Effect if local heat and moisture build-up on wear comfort of clothing. *Hohensteiner Forschungsbericht, Clothing Physiology* , 1-10.

Vimieiro-Gomes, A., Magalhaes, F., Amorim, F., Machado-Moreira, C., Rosa, M., Lima, N. & Rodrigues, L. (2005). Comparison of sweat rate during graded exercise and the local rate induced by pilocarpine. *Brazilian Journal of Medical and Biological Research,* 38, 7, 1133-1139.

Velle, W. (1987). Sex differences in sensory functions. *Perspectives in Biology and Medicine,* 30, 4, 490-522.

Wang, Z., LI, Y., Kowk, Y. & Yeung, C. (2002). Mathematical simulation of the perception of fabric thermal and moisture sensations. *Textile Research Journal,* 72, 4, 327-334.

Warner, R.R., Myers, M.C. & Taylor, D.A. (1998). Electron probe analysis of human skin: determination of the water concentration profile. *Journal of Investigative Dermatolog*y, 90: 218–224.

Wilder, J. (1962). Basimetric approach (law of initial value) to biological rhythms. *Annals of the New York Academy of Sciences,* 98, 4, 1211-1220.

Winslow, C.E.A. & Herrington, L.P. (1949). Temperature and Human Life. *American Journal of Public Health,* 40, 2, 214-215.

Winslow, C.E.A., Herrington, L.P. & Gagge, A.P. (1937). The physiological reactions of the human body to varying environmental temperatures. *American Journal of Physiology,*120, 1-22.

Winslow, C.E.A., Herrington, L.P. & Gagge, A.P. (1939). Physiological reactions and sensations of pleasantness under varying atmospheric conditions. *ASHVE,* 44, 179-194.

Wong, A.S.W., Li, Y. & Yeung, K. (2005). The influence of thermal comfort perception on consumer's preferences to sportswear. In: Y. Tochihara, Y. & Tadakatsu, O. (eds.) *Elsevier Ergonomics Book Series,* Elsevier, pp. 321-328.

Zhang, H., Huizenga, C., Arens, E. & Wang, D. (2004). Thermal sensation and comfort in transient non-uniform thermal environments. *European Journal of Applied Physiology,* 92, 6, 728-733.

Appendix A

Loughborough University

Name/Number ....……….

Health Screen Questionnaire for Study Volunteers

Note to Investigators: This HSQ can be used in its entirety but you can also remove some of the questions if you know they are not relevant to your study.

As a volunteer participating in a research study, it is important that you are currently in good health and have had no significant medical problems in the past. This is (i) to ensure your own continuing well-being and (ii) to avoid the possibility of individual health issues confounding study outcomes.

If you have a blood-borne virus, or think that you may have one, please do not take part in this research ***[only include for projects involving invasive procedures].***

Please complete this brief questionnaire to confirm your fitness to participate:

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

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

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

(a) consult your GP .... Yes ☐ No ☐
(b) attend a hospital outpatient department .... Yes ☐ No ☐
(c) be admitted to hospital .... Yes ☐ No ☐

3. **Have you ever** had any of the following:

(a) Convulsions/epilepsy .... Yes ☐ No ☐
(b) Asthma .... Yes ☐ No ☐
(c) Eczema .... Yes ☐ No ☐
(d) Diabetes .... Yes ☐ No ☐
(e) A blood disorder .... Yes ☐ No ☐

(f) Head injury .... Yes ☐ No ☐
(g) Digestive problems .... Yes ☐ No ☐
(h) Heart problems .... Yes ☐ No ☐
(i) Problems with bones or joints .... Yes ☐ No ☐
(j) Disturbance of balance/coordination .... Yes ☐ No ☐
(k) Numbness in hands or feet .... Yes ☐ No ☐
(l) Disturbance of vision .... Yes ☐ No ☐
(m) Ear / hearing problems .... Yes ☐ No ☐
(n) Thyroid problems .... Yes ☐ No ☐
(o) Kidney or liver problems .... Yes ☐ No ☐
(p) Allergy to nuts .... Yes ☐ No ☐

4. **Has any,** otherwise healthy, member of your family under the

age of 35 died suddenly during or soon after exercise? .... Yes ☐ No ☐

If YES to any question, please describe briefly if you wish (eg to confirm problem was/is short-lived, insignificant or well controlled.)

....
....
....

5. **Allergy Information**

(a) are you allergic to any food products? Yes ☐ No ☐
(b) are you allergic to any medicines? Yes ☐ No ☐
(c) are you allergic to plasters? Yes ☐ No ☐

If YES to any of the above, please provide additional information on the allergy

……………………………………………………………………………………………
………

5. **Additional questions for female participants**

(a) are your periods normal/regular? .... Yes ☐ No ☐
(b) are you on “the pill”? .... Yes ☐ No ☐
(c) could you be pregnant? .... Yes ☐ No ☐
(d) are you taking hormone replacement therapy Yes ☐ No ☐

(HRT)? ☐ ☐

6. Please provide contact details of a suitable person for us to contact in the event of any incident or emergency.

Name: ……………………………………………………………………………………………… ………

Telephone Number: ……………………………………………………………………………………………… ………

Work ☐ Home ☐ Mobile ☐

Relationship to Participant:……………………………………………………………………………… ……….

7. Are you currently involved in any other research studies at the University or elsewhere?

Yes ☐ No ☐

If yes, please provide details of the study

……………………………………………………………………………………………… ……………………………………………………………………………………………… ………………

Appendix B

Loughborough University

INFORMED CONSENT FORM

(to be completed after Participant Information Sheet has been read)

Investigation of regional skin wettedness on local and whole body thermal comfort.

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 C

Pilot test: Does the amount of sweat and concentration of NaCl influence GSC?

Introduction

Galvanic skin conductance (GSC) is a measure of how well the skin can conduct a small electrical current and is known to be influenced by sweat production within the glands, skin hydration and the amount of sweat present on the skin surface (Edelberg, 1972). From research, it is apparent that GSC measured will be not only be influenced by the amount of sweat produced but also by the composition of the sweat (Gibson, 1963). Figure 1 illustrates the basic components of the skin structure and a circuit components model indicating the areas which contribute to the resistance. However, the degree to which the measurement is influenced by sweat on the skin surface (label E1), sweat within the skin (D1) and within the sweat gland (SD1) is unknown. The extent to which sweat on the surface affects GSC whilst SD1 and D1 are absent of sweat will be investigated in this study. This will be achieved by keeping the sweat glands inactive by exposing participants to a cold room during rest whilst artificial sweat will be sprayed onto the skin surface. As the concentration of sweat is known to influence conductance, sweat of varying concentrations of sodium chloride (NaCl) will also be investigated.

To further the understating of this measurement, one other factor will be investigated, which is not linked to sweat, but may influence GSC, namely skin blood flow (SkBf). The movement of fluid within the measurement area potentially could influence conductance, therefore vasodilatation and vasoconstriction will be briefly checked as a precaution.

Aim

The aim of this study is to address whether the amount of artificial sweat and the concentration of artificial sweat sprayed onto the skin surface would influence GSC. The influence of SkBf on GSC was also assessed in this experiment.

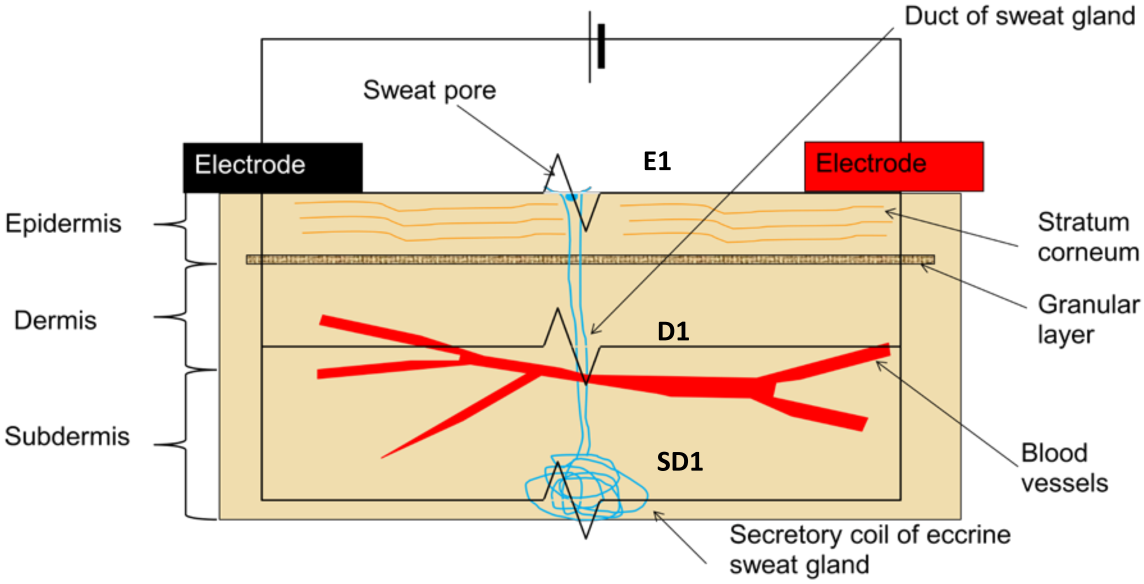


Figure 1: Illustration of some basic components of the skin structure and a circuit of components model indicating the areas which contribute towards the resistance/conductance of the skin.

Methods

Participants

Five participants (two male, three female) were recruited for this trial.

Clothing

Each participant dressed in the required clothing, which consisted of running shorts, plus a sports bra for females and his/her own personal socks and athletic trainers.

Methodology

Upon arrival to the laboratory the participants' height and weight were recorded and blood pressure measured (Omron MX2-BASIC). The test areas included the upper arm and the scapula which were cleaned with deionised water to remove any chemical agents including electrolytes from sweat already on the skin surface. The tests areas were then prepared with electrodes for the measurement of GSC (Biopac) and a Laser Doppler flow meter (Moor Labs Instrument) to measure SkBf at the upper arm (only). The electrodes on the upper back were covered by a plastic impermeable case and glued to the skin (using Collodion). This was done to prevent any of the artificial sweat leaking underneath the electrode and influencing the contact area. Participants then sat in an environmental chamber (18°C, 40% RH) and baseline values were recorded for two minutes. Following this blood flow to the upper arm was occluded by applying a pressure cuff inflated no higher than 50 mmHG above systolic pressure for 2 minutes. Vasodilatation was then instilled via local heating plates located around the Doppler flowmeter set to 40°C. Local heating was applied for no longer than 3 minutes.

Participants then lay in the prone position whilst artificial sweat of different concentrations of NaCl and different quantities were sprayed onto the scapula. The concentrations of NaCl and the quantity of sweat applied to the skin are listed in Table 1, the order was randomised. The solutions were kept in a water tank at 34°C to mimic that of skin temperature and sprayed onto the skin, left for 1 minute after which the area was dried with a towel. One minute periods were allowed between each surface spray.

Table 1: Concentration and quantities of 'artificial' sweat.

Concentrations	Quantity (g)	Concentrations	Quantity (g)	Concentrations	Quantity (g)
Deionised water	77	127 mmol/L^{-1} NaCl	77	250 mmol/L^{-1} NaCl	77
Deionised water	121	127 mmol/L^{-1} NaCl	121	250 mmol/L^{-1} NaCl	121
Deionised water	242	127 mmol/L^{-1} NaCl	242	250 mmol/L^{-1} NaCl	242

SkBf is expressed as a percentage of maximal skin blood flow either obtained from values post circulatory occlusion or from local heating using the following equation:

$$\%\max\ of\ SkBf = \frac{SkBf_{ix}}{SkBf_{max}} \cdot 100$$

Where,

%max of SkBf	percentage of maximal skin blood (%)
$SkBf_{ix}$	raw value of obtained from the subject (i) in a given situation (x) (PU)
$SkBf_{max}$	Maximum value of skin blood flow obtained (Pu)

Results

The aim of this pilot test was to address whether the amount of artificial sweat and the concentration of artificial sweat sprayed onto the skin surface would influence GSC. The influence of SkBf on GSC was also assessed in this experiment. Figure 2 a-b illustrates the raw data measured for GSC (GSC_{raw}) at the upper back and upper arm respectively. In Figure 2a, the shaded area indicates when artificial sweat was sprayed onto the skin surface. GSC at the upper back (Figure 2a) decreased during this time, but the value range is very small, suggesting no influence of surface sweat on GSC. Figure 2b illustrates GSC_{raw} at the upper arm and the shaded area indicates the period of vasoconstriction and vasodilatation, but conductance does not differ between the two responses and remains stable.

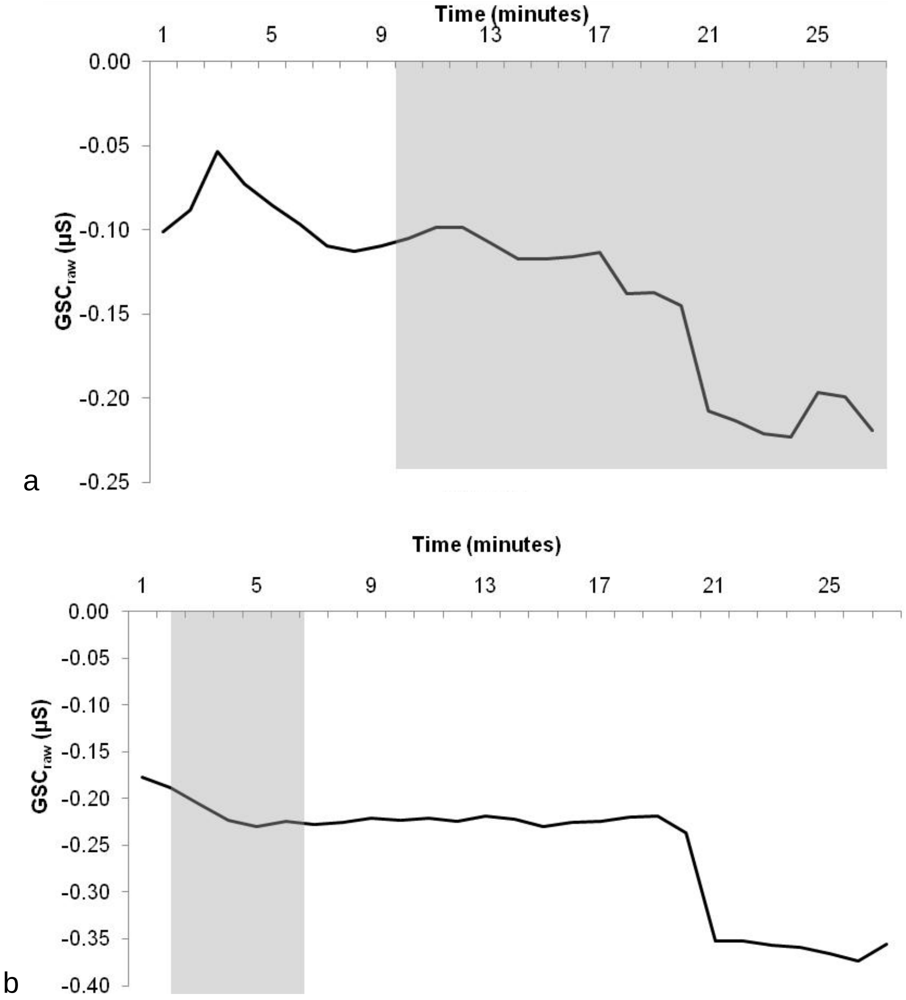


Figure 2: a) GSC_{raw} at the upper back. Shaded area indicates the period of spraying artificial sweat. B) GSC_{raw} at the upper arm. Shaded area indicates the period of vasoconstriction and vasodilatation to the forearm.

Artificial sweat was sprayed onto the skin surface in a randomised order. Therefore, the influence of the amount of sweat and its quantity of NaCl on GSC_{raw} will be analysed according to its change from the values recorded the minute prior to each spray. The results are presented in Figure 3, where it can be seen that the amount of deionised water on the skin did not influence GSC_{raw}. Overall the various quantities of sweat and concentrations of NaCl did not have a large influence on the measurement. Two-way repeated measures ANOVA revealed no significant effect of quantity or concentration of NaCl of artificial sweat on GSC_{raw}.

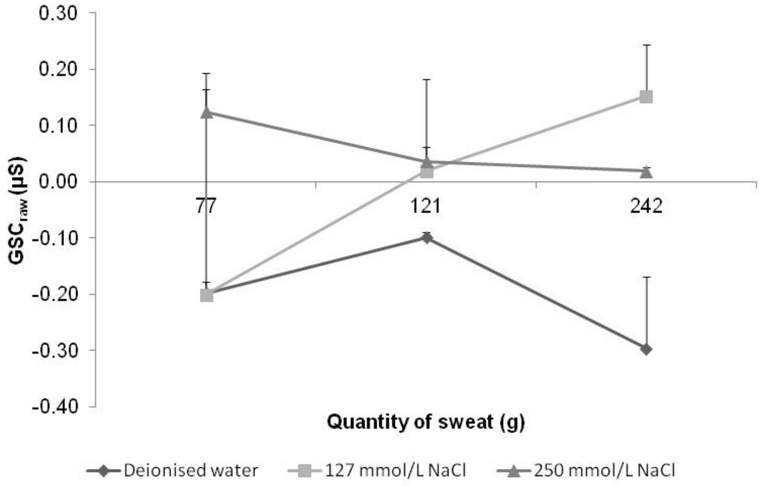


Figure 3: GSC_{raw} after spraying various quantities (77g, 121g and 242g) of artificial sweat of various concentrations of NaCl (deionised water, 127 mmol·l^{-1}, 250 mmol·l^{-1}).

Discussion

During the test, sweat production was inhibited by exposing participants to cold environments and keeping them inactive. This ensured minimal activity in D1 and SD1 in Figure 1 which then allowed for an investigating of the influence of various quantities of surface sweat on E1 (Figure 1). The quantities of sweat were chosen so that the areas surrounding the electrodes were covered with a large amount of sweat (approximately 77g, 121g and 242g). The concentration of NaCl within these samples varied from deionised water (no NaCl) to very high concentrations (127mmol·L^{-1} and 250mmol·L^{-1}). These values exceed those found in previous research by Patterson et al. (2000) in order to elicit maximal responses in the GSC measurement. Slight differences were found in GSC depending on the quantity and concentration sprayed on the skin, however no significant differences in GSC_{raw} were found. Alongside this, the changes that did occur were much lower than values obtained from chapter 6, 7, 8 and 9 and covered a very small range.

The results presented Figure 2 and Figure 3 display GSC_{raw} and suggest changes over the course of the study. If the presence of sweat influences the measurement then it is likely that the higher the quantity of sweat the greater the increase in GSC. The results suggest that the largest quantity of sweat (~242g) on the surface caused the smallest change in GSC. Mixed findings from the lowest (~77g) and middle (~121g) quantities were observed with 77g of sweat comprised of 127mmol·L^{-1} causing a greater change in conductance whilst 121g of deionised water also caused a great change in conductance. As research into the diagnosis of cystic fibrosis proves that large quantities of NaCl in sweat causes a large increase in conductance one would expect the solution containing the highest concentration of NaCl to have a large influence on the measurement. The deionised solution did not show any changes in conductance in all quantities of 'sweat' on the skin. In general the solution containing 127 mmol·L^{-1} of NaCl had the largest influence on conductance and the highest concentration (250mmol·L^{-1}) only had the largest influence with 77g surface sweat. However, regardless of this data, in comparison to previous studies whereby sweat production was high and surface sweat was in abundance, the values of GSC obtained here are much lower and cover a very small range.

To determine whether SkBf had an influence on GSC, blood flow to the arm was occluded using a pressure cuff and vasodilation was induced via local heating to 40°C. Skin blood flow began to increase at ~4 minutes with the local heating applied between the electrodes. Skin blood flow began to increase prior to this and continued to increase with local heating after occlusion. The influence of local heating on the sweat glands may explain the small increment in GSC, but interesting GSC reached its peak when SkBf was beginning to increase and did not correspond with peak SkBf. When SkBf was at its peak, GSC was reducing to below zero. As stated earlier, very small changes in GSC occurred and any changes are likely to be a result of noise in the data.

Conclusions

To conclude, GSC is not influenced by the quantity of sweat on the skin surface between the electrodes, nor the concentration of NaCl in the sweat. Alongside this, changes in SkBf also have no influence on the measurement of GSC. GSC must therefore be influenced by sweat produced in the glands and sweat within the epidermis. However, sweat directly underneath the contact area of the electrode may still influence the measurement.