Regional Sweat Rates in Humans

by

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ABSTRACT

Exposures to hot environments and high intensity exercise provide some of the greatest challenges to the thermoregulatory system. Under such conditions evaporation is the greatest avenue of heat loss from the body. Whilst regional sweat rate variations in humans are widely recognised, most studies only measure a small number of sites using a limited surface area, and generalise this data to larger regions A consensus in the literature indicates that the highest sweat rates are on the forehead and torso, and lowest on the extremities. However, no study has quantitatively measured regional sweat rates over large surface areas of the body. Since sweating is related to the thermal state of the body, comparison of regional sweat rates between studies is further complicated by the use of different environmental conditions, exercise modes and work rates. A good meta-analysis of existing data is therefore problematic

The aim of this thesis was to produce detailed whole body sweat maps for male and female athletes, and untrained males, during two exercise intensities in moderate environmental conditions (25°C, 50% *rh*) with a 2 $m.s^{-1}$ air velocity. An initial study to assess the effect of the presence and direction of wind on regional sweat rates was also conducted. A modified absorbent method of sweat collection was used to simultaneously measure large areas of the skin, with all absorbent pads specific in size to each participant. Sweat mapping was completed progressively over three experiments with a limited duration of pad application to prevent altering the thermal state of the body or inducing hidromeiosis. A comparison of both regional and gross sweat loss between genders and between individuals of differing cardiovascular fitness was conducted. Variation in regional sweat rate was also measured in male athletes following six consecutive days of dry-heat acclimation (45°C, 20% *rh*) using a controlled hyperthermia technique

Despite large inter and intra individual variation in both gross and absolute regional sweat losses, consistent patterns of distribution were observed both within and between all groups No significant change in distribution of sweat occurred with wind condition, however absolute sweat rates were significantly higher in the absence of wind. During sweat mapping, the highest sweat rates were observed on the central and lower back and the lowest were observed on the fingers, thumbs, and palms Sweat mapping of the head in male athletes also demonstrated high sweat rates on the forehead and low sweat rates on the chin and cheeks relative to the rest of the body. Sweat rate increased significantly in all regions from the low to high exercise intensity, with exception to the feet. Male athletes exhibited significantly higher gross and regional sweat rates than female athletes for the same relative work rate at the lower exercise intensity Female athletes had a significantly higher regional distribution of sweat towards the extremities compared to male athletes, indicating a greater sweating efficiency. No significant differences in the regional distribution of sweat were observed between trained and untrained males Gross and absolute regional sweat loss increased significantly following six days of hot-dry heat acclimation Relative sweat rates increased significantly on the arms during the higher exercise intensity, indicating a possible move towards uniformity of sweating No correlation was observed between regional sweat rate and regional skin temperature in any group or following heat acclimation.

This thesis has confirmed the presence of consistent patterns of regional sweat rate in Caucasians adults and further demonstrated very large intra regional variation.

Keywords: Thermoregulation, sex, sweating, exercise, metabolic rate, heat acclimation, regional, skin temperature, sweat mapping

Statement

The work presented in this thesis was funded by both the Department of Human Sciences, Loughborough University and Adidas. The data collected in this thesis was in part used in the development of Adidas 'Clima365' sports clothing.

Study 1 was conducted jointly by the author and Mr J Dovey. The author assisted in the supervision of Mr J Dovey as part of his BSc dissertation work. The author designed the experiment and reanalysed the raw data for inclusion in this thesis.

Study 2 was conducted jointly by the author and Mr P Manners The author provided supervision for Mr P. Manners during his BSc dissertation work and was responsible for the design of the experiment The raw data were reanalysed by the author for inclusion in this thesis.

Study 3 was extended with the addition of six participants as part of a final year dissertation. The author was responsible for the design of the experiment and assisting in the supervision of Miss V Holland The author reanalysed the raw data for inclusion in this thesis

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Publications

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Havenith, G., Smith, C., and Fukazawa, T. (2008) The skin interface – Meeting point of physiology and clothing science. International Symposium of Textile Bioengineering and Informatics (TBIS 2008), Hong Kong

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Notation and Abbreviations

a_c, area of control material (cm^2)
bw, back wind direction condition
BF, body fat (%)
BL, Baseline measurement
C, convective heat loss per unit area ($W.m^{-2}$)
C_{res}, dry respiration heat loss per unit body surface area ($W.m^{-2}$)
Db, total body density (g/cc)
E, evaporative loss per unit body area ($W\ m^{-2}$)
E_{sk}, evaporative loss from the skin per unit body surface area ($W\ m^{-2}$)
E_{max}, maximum evaporative potential per unit area ($W\ m^{-2}$)
E_{req}, required evaporative loss per unit area for heat balance ($W\ m^{-2}$)
E_{res}, evaporative loss from respiration (W)
fw, front wind direction condition
GSL, gross sweat loss (g, $g\ h^{-1}$, or $g.m^{-2}.h^{-1}$)
h_c, convective heat transfer coefficient ($W\ m^{-2}\ °C^{-1}$)
h_e, evaporative heat transfer coefficient ($W\ m^{-2}\ kPa^{-1}$)
h_r, radiative heat transfer coefficient ($W\ m^{-2}.°C^{-1}$)
HASG, heat activated sweat gland
I1, exercise intensity 1
I2, exercise intensity 2
K, conductive heat transfer per unit area ($W\ m^{-2}$)
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)
nw, no wind condition
P_a, partial pressure of water vapour in air (kPa)
P_{sk}, partial pressure of water at the skin (kPa)
rh, relative humidity (%)
R, radiative heat loss per unit area ($W\ m^{-2}$)
S, rate of heat storage per unit area ($W.m^{-2}$)
SA, surface area (m^2)
SKF, skinfold measurements (mm)
SR, sweat rate (g, $g\ h^{-1}$, or $g.m^{-2}.h^{-2}$)
t, time (s)
T_a, air temperature (°C)
T_{core}, core temperature (°C)
T_{re}, rectal temperature (°C)
T_{sk}, skin temperature (°C)

$\overline{T}_{sk}$, mean skin temperature (°C)
v, air velocity (m s^{-1})
V, speed of walking (m s^{-1})
$VO_{2\,max}$, maximal oxygen uptake (ml.min^{-1} kg^{-1})
w, skin wettedness (ND)
w_b, body weight (kg)
w_c, weight of control material (g)
w_d, dry weight of pad/cotton (g)
W, mechanical work (W.m^{-2})
$\overline{T}_{sk}$, mean skin temperature (°C)
η, terrain factor (η= 1 0 for treadmill)

Chapter 1

Introduction and Review of Literature

1 Introduction

The human body strives to maintain an internal temperature of approximately 37°C, fluctuating within narrow limits. Humans are able to tolerate internal temperatures from 35 to 41°C for limited periods, beyond which physical illness and ultimately death can occur. Interaction with several body systems allows the body to maintain internal temperature within acceptable limits (Kenney, 1998) Variation in individual characteristics determines the ability of the body to thermoregulate, including $VO_{2\,max}$, acclimation state, body composition, gender, age, hydration state, and circadian rhythm (Havenith and Van Middendorp, 1990, Havenith, 1990, 1997, 2001a, 2001b) The influence of these parameters on core (T_{core}) and skin temperature (T_{sk}) can be assessed through sweating, vasodilatation/constriction, and cardiac output

High ambient temperatures and exercise provide some of the greatest challenges for the thermoregulatory system Under such conditions, evaporation of sweat is the greatest avenue of heat loss from the body. Sweating is known to vary between sexes, in trained and untrained individuals, between races, and even within individuals from day to day. Global sweating has been extensively reviewed within the literature, however less information is available regarding regional variation over the body. This thesis will focus on this regional variation in sweat rate (SR), and explore it in differing groups; male and female athletes, untrained males, and acclimated male athletes. To introduce the important concepts in thermoregulation, this chapter will review general environmental and individual parameters influencing the control of body temperature. A detailed discussion of sweat gland structure and function, control of sweating, and data available regarding distribution over the body will further be presented

1.1 Heat Balance

Humans are exposed to considerable changes in their external environment but maintain an internal body temperature which is largely independent of environmental conditions (Nielsen, 1938; Hardy, 1961, cited in Stitt, 1993). This does not mean that the environment has no impact upon thermoregulation, in fact mechanisms controlling body temperature rely on input from the environment to control heat exchange to and from the body. The thermal environment to which humans respond is defined by six interacting parameters; four environmental parameters, (humidity, air movement, air temperature, and radiant temperature) and two personal parameters, (metabolic heat and clothing) There is a heat balance between the body and the environment, whereby heat production and transfer must be balanced by heat output to maintain body temperature within narrow limits. The dynamic equilibrium which occurs between heat loss and heat gain from the body can be expressed as a conceptual heat balance equation (Parsons, 2003), as illustrated in equation (1.1)

$$M - W = E + R + C + K + S \qquad (1\ 1)$$

Where:

M, metabolic rate ($W.m^{-2}$)

W, mechanical work ($W\ m^{-2}$)

K, heat loss by conduction ($W\ m^{-2}$)

C, heat loss by convection ($W.m^{-2}$)

R, heat loss by radiation ($W.m^{-2}$)

E, heat loss by evaporation ($W\ m^{-2}$)

S, heat storage ($W\ m^{-2}$)

For the body to be in a state of heat balance, characterised by constant body temperature (T_{body}), which is often defined as a weighted average temperature of both T_{core} and T_{sk}, the rate of heat storage must be zero. When a net gain in heat occurs T_{core} will rise as a result of positive heat storage. The opposite is true in the presence of net heat loss resulting in negative heat storage and a decrease in T_{core}. When considering heat loss from the body in warm environments, K, C, and R are less effective compared to evaporation The evaporation of sweat from the surface of the skin provides the greatest

avenue of heat loss from the body in hot environments and during exercise (Kerslake, 1972; Stitt, 1993) Evaporation of sweat occurs when sufficient heat from the skin causes water to change from liquid to gas. This process requires 2430 joules per gram ($J.g^{-1}$) of water at 30°C (Gibson and Charmchi, 1997) and is an extremely effective cooling mechanism when the skin remains wet due to high levels of sweat production (Gagge, 1937; Candas *et al.*, 1979a, 1979b, Candas, 1986). In addition to 'visible sweating', 20-25 ml of water per hour evaporates through the surface of the skin and the alveolar surfaces of the lungs as 'insensible perspiration' The rate of insensible perspiration remains fairly constant throughout the day, accounting for approximately one-fifth of the average daily heat loss from the body (Kuno, 1956).

1.1.1 Air Temperature, Air Velocity and Relative Humidity

In high ambient temperatures (T_a) both T_{sk} and T_{core} rise as T_a increases, resulting in heat storage and the requirement of the body to lose this 'extra' heat Peripheral blood vessels dilate to increase T_{sk} and thereby sensible heat loss $(R+C+K)$, and sweating is stimulated Under such conditions, sensible heat loss is minimal and a reversal in the temperature gradient between the body and the environment $(T_{sk}-T_a)$ may be observed, as the temperature gradient that drives K, C, and R will be small or even directed towards the body Insensible heat loss therefore becomes of great importance; the greater the increase in body temperature the higher the *SR* (Kuno, 1956) Sweat evaporates from the surface of the skin to lower body temperature, a process often made more effective in the presence of air movement (Nishi and Gagge, 1970; Saunders *et al.*, 2005). Convective heat loss from the surface of the skin is affected by two factors; firstly by the presence of air movement, affecting the convective heat transfer coefficient, and secondly by the temperature gradient between the skin surface and the surrounding environment $(T_{sk}-T_a)$, as observed in equations (1.2) and (1 3) respectively:

$$h_c = 8.3 \cdot \sqrt{v} \qquad (1\,2)$$

$$C = h_c \cdot (t_{sk} - t_a) \qquad (1.3)$$

Where;

(h_c), convective heat transfer coefficient (W $m^{-2}.°C^{-1}$)

(v), air velocity (m s^{-1})

$(T_{sk} - T_a)$, temperature gradient between T_{sk} and T_a (°C)

When v is greater than 0.2 $m.s^{-1}$, disruption to the boundary layer of air surrounding the skin occurs and convective heat loss increases. Due to the dependence of convective heat loss upon the $T_{sk} - T_a$ gradient, cooler air will increase the rate of convective heat loss whilst warmer air will reduce it, or potentially result in heat gain in high temperatures (Dennis and Noakes, 1999; Parsons, 2003, pp16-20) If v is very high, sweat may be removed from the surface of the skin as liquid very rapidly and before the heat can be removed Such a phenomenon is not desirable for efficient heat loss via evaporation

Another important factor affecting the rate of evaporation is humidity. The driving force for evaporation of sweat from the surface of the skin is the difference between the partial vapour pressure at the skin surface (P_{sk}) and the environment (P_a) As the $P_{sk} - P_a$ gradient decreases, the potential amount of evaporation will be reduced (Parsons, 2003). In hot-dry environments heat loss via evaporation of sweat can account for as much as 85-90% during exercise (Armstrong 2000) In hot-wet environments, evaporative heat loss may be limited, causing a great challenge to the thermoregulatory system The saturated vapour pressure is the vapour pressure at which the air can hold no more water vapour, and is dependent upon T_a the higher the T_a, the greater the amount of water vapour that can be held in the air, and therefore the greater the partial vapour pressure (Parsons, 2003).

1.1.2 Core and Skin Temperature

When considering body temperature the conceptual 2 part model which identifies 'core' and 'shell' temperature is widely used. T_{core} may be regarded as the temperature of the deep tissues of the body, including the trunk, neck and brain It is this which the thermoregulatory system must maintain at approximately 37±2°C, allowing changes

only within narrow limits for the maintenance of optimal functioning 'Shell' temperature is recognised as the temperature of the outer, more superficial tissues of the body, including the limbs and the superficial tissues of the head and neck Variation occurs with both internal thermoregulation and external environmental conditions, and shell temperature shows a wider range of temperatures without impairment of functioning (Lind, 1963; Kerslake, 1972). Unlike T_{core}, shell temperature is usually taken as a mean over a number of sites, commonly using a system of weighting for each individual value (Ramanathan, 1964).

Core temperature is normally taken at a single site, for example rectal temperature, yet considerable regional variation in the 'core' exists which has lead to controversies in literature over the usefulness of different sites (Stitt, 1993). When considering neural factors in thermoregulation, hypothalamic temperature is the preferred expression of core body temperature This region is highly sensitive to its local temperature change and subsequent control of autonomic thermoregulatory responses (Hammel, 1968) Under conditions of heat stress brain temperature can differ from other core body regions but is an impossible site of measurement in humans, making it impractical in experimentation Oesophageal and rectal temperature are more commonly used as an indication of T_{core} although both have their disadvantages. In particular Oesophageal temperature requires suppression of the gag reflex during insertion which may not be possible in some subjects Rectal temperature has been criticised for a low level of systemic perfusion of the pelvis causing thermal inertia, and an artificially elevated temperature during exercise resulting from a preferential venous drainage from the legs. (Stitt, 1993)

A widely accepted concept that T_{core} is independent of environmental stress over a wide range of conditions (the 'prescriptive zone') in steady state, and only depending upon rate of work, was originally established through the classic work of Lind (1963) When environmental conditions become extreme, regulation of T_{core} is challenged In a constant environment a strong correlation is expected between SR and T_{core} when work rate is altered. Under these conditions there is little change in T_{sk}, hence required evaporative heat loss increases in relation to heat production, similarly to T_{core}. Under

conditions outside of the 'prescriptive zone' T_{core} will rise with environmental conditions regardless of a constant work rate, showing a correlation between T_{core} and sweat rate. This correlation is not present under a constant work rate in the 'prescriptive zone', where T_{core} is virtually independent of the environment (Lind, 1963), as observed in Figure 1 1

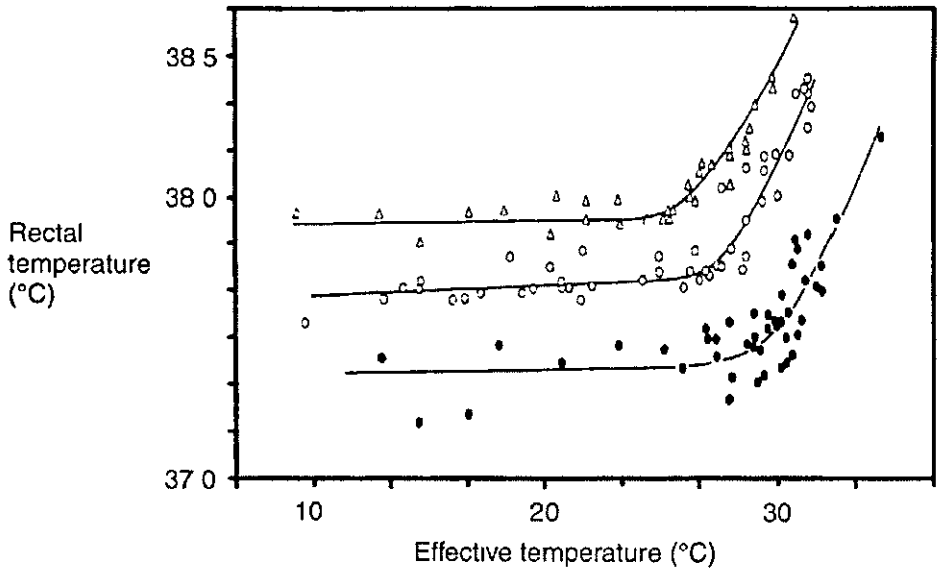


Figure 1.1. Equilibrium rectal temperatures of one subject working at energy expenditures of 180 (•), 300 (□) and 420 (Δ) kcal h^{-1} in a wide range of climatic conditions (Reproduced from Lind, 1963)

Three main categories identified by the ability of humans to tolerate heat are defined by Lind (1963), 1) the prescriptive zone, whereby thermal equilibrium may be attained independently of the environment, 2) the compensatory zone, in which thermal equilibrium is achieved but at the cost of increased physiological strain evoking compensatory physiological mechanisms, 3) the intolerable zone, in which thermal equilibrium cannot be achieved (Lind, 1963)

1.1.3 Thermal Gradients and Heat Loss

Thermal gradients exist both within the body and between the body's surface and the environment Only when a temperature gradient is maintained between the skin and the surrounding environment can heat loss via non-evaporative mechanisms occur. Metabolic heat produced by cells in the body is dissipated via conduction to the surrounding tissue and by convection via the flow of extracellular fluid, primarily blood

The result is a dynamic exchange of heat throughout the body which is dependent upon the physiological properties of the tissue, for example density, thermal conductivity, and specific heat of the cells. The net heat transfer from the core to the skin allows the loss of heat to the environment via K, C, R, and E from the surface of the lungs and, if present sweat from the surface of the skin. The thermal properties of muscle, fat, blood, etc are clearly very important in the 'passive' system of thermoregulation. The 'dynamic' system of thermoregulation is required to control this passive system in conditions of changing external environment, however, it is important to remember that these systems do not act independently but as a 'whole' (Fiala *et al*, 1999, 2001, Wendt *et al*, 2007).

The relationship of heat transfer from the body core to the environment is reversed when T_a exceeds T_{sk}, resulting in the body gaining heat via mechanisms previously discussed At this point, evaporation of sweat from the surface of the skin becomes the greatest avenue of heat loss from the body Evaporative cooling power is dependent upon the gradient between the saturated water vapour pressure at the observed skin temperature (P_{sk}) and partial pressure of water vapour in air (P_a), and air velocity (discussed in section 1.1.1). When SR exceeds the maximum evaporative potential (E_{max}), sweat drips from the skin and is no longer of benefit in the loss of heat from the body (Winslow *et al*, 1937; Gagge, 1937; Candas *et al*, 1979a, 1979b, Candas, 1986, Wendt *et al*, 2007) This is of particular importance when exercising in hot, humid environments where the environment cannot accommodate the levels of evaporation required for sufficient heat loss. Heat storage in the body may rise to critical levels resulting in impaired physical performance and possible heat stress (Taylor, 2000, Taylor and Cotter, 2006; Wendt *et al*, 2007)

1.2 Thermoregulation

Mechanisms of thermoregulation are complex and still under debate, with precise neural pathways still not fully understood (Shibasaki *et al*, 2006) Traditionally, the body has been considered to regulate body temperature within narrow limits around a hypothalamic set point of 37°C. Some authors regard thermoregulation in terms of 'heat regulation' rather than temperature regulation, determined by body heat storage, heat

gains and heat losses (Adolph, 1979; Webb, 1995) Metabolic rate constantly changes to meet energy demands with concomitant changes in body heat storage resulting from a lag in heat loss. Heat loss is regulated through vasodilatation and sweating to achieve a new steady state in conditions of high ambient temperature and during exercise (Gagnon *et al.*, 2008).

1.2.1 Central and Peripheral Control

It is widely accepted that the central thermal controller is located in the preoptic hypothalamus (Bazett, 1958, cited in Sargent, 1962, pp 152, Benzinger, 1959, 1961) Sensory input is received from both deep body and peripheral thermoreceptors Central thermoreceptors are located in the hypothalamus itself and in a number of organs These receptors are sensitive to changes in deep body temperature compared to input regarding environmental temperature provided by peripheral thermoreceptors in the skin (Kenshalo, 1979, Gleeson, 1998). Deep thermoreceptors are of greater importance in controlling T_{core} than peripheral input, with the relative contributions of the two inputs being approximately 9·1 for T_{core} and T_{sk} respectively (Nadel *et al* , 1971a, 1971b)

Classically, central mechanisms have been viewed to regulate body temperature by integrating complex neural signals from deep and peripheral tissues of the body. Following stimulation of the thermoregulatory centre in the hypothalamus, alterations of both the heat production of the body and heat exchange with the environment occur; these processes may be supported by behavioural modifications When T_{core} drops below a desirable level the heat gain centre in the preoptic posterior hypothalamus is stimulated and the heat loss centre in the preoptic anterior hypothalamus is inhibited (Mekjavic and Eiken, 2006) Vasoconstriction of peripheral blood vessels is initiated to redirect blood to the core, reducing heat loss from the body via K, C, and R. In conjunction with heat conservation mechanisms, shivering thermogenesis and nonshivering thermogenesis are initiated to increase heat production within the body. The former involves brief contractions of skeletal muscles, increasing heat production by as much as 400 percent The latter stimulates the release of epinephrine from the adrenal gland to increase metabolic activity in tissues throughout the body Conversely, when body temperature becomes elevated to an unacceptable level, heat loss centres in

the brain are stimulated to promote heat loss via a number of mechanisms and heat gain centres are inhibited (Benzinger 1959). The smooth muscles of peripheral blood vessels relax to allow an increase in blood flow to the skin, redirecting warm blood away from specific organs in the body's core. A resultant increase in T_{sk} allows the excess heat to dissipate into the surrounding environment by radiation and convection (Armstrong, 2000). If vasomotor adjustments are insufficient to meet the demands for heat loss, sweating is stimulated (discussed in detail in Section 1 2 2) As described, the stimulation or suppression of the heat loss and heat gain centres in the anterior and posterior preoptic hypothalamus respectively, explains the antagonistic functions of sweating and shivering

Considerable debate still surrounds the mechanisms of thermal balance which maintain T_{core} around a 'set point' temperature. Some authors refute the concept of a set point regulation but rather the maintenance of T_{core} within a narrow range, allowing fluctuation Traditionally, thermoregulatory models have explained the regulation of body temperature about a set point (Hammel *et al* , 1963, Hammel, 1968) Engineering models have been developed for the understanding of thermoregulation, assuming a reference temperature, an error signal, and appropriate effector responses to minimize the error signal There is however debate as to whether an actual set point temperature exists. Huckaba *et al* , (1971) proposed a control system based upon a single set point in the hypothalamus. They suggested vasomotor, sudomotor and metabolic responses as three parallel control loops, activated by central or peripheral receptors either separately or working in combination Other authors have suggested independent set points for both hypothalamic temperature and T_{sk} (Stolwijk and Hardy, 1966) Banerjee and colleagues (1969) further suggest not only absolute T_{sk} but the rate of change of T_{sk} as a factor in thermoregulatory control Bazett (1951) identified thermoreceptors at differing depths of the skin, indicating the ability to sense heat flow. This was later confirmed by Ivanov and colleagues (1982; 1987, cited in Webb, 1995) who demonstrated that changes in the transcutaneous thermal gradient affected thermoregulatory responses

When considering set point, careful attention must be drawn to the definition used by authors Traditionally it has been viewed as a single temperature point, however more

recent definitions in thermal physiology suggest a threshold zone reflecting a range of T_{core} between thresholds for sweating and shivering (Mercer, 2001). The adjustment of the set point has also been highlighted, varying with T_{core} thresholds and gains in vasomotor and sudomotor responses (Mekjavic and Eiken, 2006)

The initial response of the body against a change in ambient temperature is the stimulation of vasomotor adjustments It seems physiologically unnecessary for sweating or shivering responses to be initiated immediately upon deviation from a set point value It would be more energetically efficient for T_{core} to fluctuate with heat exchange with the environment through vasomotor adjustment (Mekjavic and Eiken, 2006). The narrow range of temperatures within which T_{core} may be controlled in the absence of metabolic or sudomotor adjustments is defined as the thermoneutral zone (Mercer, 2001) Once the capabilities of the vasomotor system to control T_{core} are exceeded, autonomic responses are activated at a T_{core} representing the thermoeffector threshold. Similarly to the thermoneutral zone for ambient temperature, an 'interthreshold zone' exists for T_{core} in which autonomic responses for heat loss (sweating) or heat production (metabolic) are not induced Both the thermoneutral and interthreshold zones may be modified by non thermal factors, altering the individual thresholds for vasomotor, sudomotor and metabolic responses (Mekjavic and Eiken, 2006).

Cabanac and Massonnet (1977) observed a single set point for sweating and shivering following a state of mild hyperthermia induced by immersion in 38°C water followed by cooling of participants in 28°C water. However, when this protocol was modified by Mekjavic and Bligh (1989, cited in Mekjavic and Eiken, 2006) to prevent changes in T_{core} being influenced by changes in peripheral temperature, the thresholds for sweating and shivering were found not to coincide The latter technique used exercise to increase T_{core} whilst immersing participants in 28°C to clamp T_{sk}. Following stabilisation of sweating, exercise was stopped to allow gradual hypothermia. A zone was observed in which neither sweating nor shivering were innervated The overlap of shivering and sweating onset observed by Cabanac and Massonnet (1977) was thought to result from abrupt changes in peripheral tissue and therefore peripheral blood perfusion causing

large changes in oesophageal temperature It would therefore suggest that regulation of body temperature within a narrow range of temperatures is likely, rather than a single set point

1.2.2 Non-Thermal Factors

The central controller for thermoregulation in the hypothalamus receives non thermal sensory information which act to elicit or modify thermoregulatory responses. Non thermal factors include neural input from osmoreceptors and baroreceptors, providing information regarding plasma osmolarity and blood volume. Changes in these factors affect sweating and vasodilatation responses to rises in T_{core}. Another important non thermal modulator of thermoregulation is exercise. Unlike the gradual rise in T_{core} experienced with heat application, heat generated from muscular contraction during exercise causes a more rapid elevation in T_{core} and consequent increase in sweating (Shibasaki *et al*, 2006) Exercise is a greater challenge to the thermoregulatory system than exposure to high ambient temperatures. 'During exercise heat can be produced in the working muscles at rates in excess of 1,000 Joules per second (J sec^{-1}), while in air or in well-stirred water environment heat gains exceeding 300 J sec^{-1} are difficult to obtain without burning the skin' (Stolwijk and Nadel, 1973, pp 1607) Skeletal muscle temperature can increase up to 1 5°C within the first minute of exercise This is due to more than 75% of the energy produced from skeletal muscle being released as heat due to the inefficiency of metabolic transfer. The existence of venous or muscle sensors and the degree of their sensitivity to heat production within the first few seconds of exercise is however not known (Wendt *et al*, 2007).

When an organism is exposed to heat or begins exercise, thermoregulatory mechanisms tend to 'overshoot' before adjusting to a new equilibrium adequate for the conditions Initially a reflex sweating response is stimulated to allow evaporative cooling and a large shift in blood from the core to peripheral regions occurs to increase heat loss via K, C, and R. The non thermal input from exercise has been demonstrated by a number of authors who have observed sweating within seconds of initiation of exercise without a rise in T_{core} or T_{sk} (Van Beaumont and Bullard, 1963; Stolwijk and Nadel, 1973, Yamazaki *et al.*, 1994, Shibasaki *et al*, 2006) The reflex sweating response

appears prominent at the beginning of exercise, however as steady state work continues SR is controlled predominantly by thermal factors, in particular core temperature or hypothalamic temperature Since T_{core} is a primary stimulus in heat acclimation, athletes who regularly experience high T_{core} values during training develop a degree of acclimation (see section 1.2.3.1) The decrease in heart rate and ventilation observed with an increase in cardiovascular fitness, and a higher SR for a particular T_{core} provide an increased ability to cool the body (Nadel *et al* , 1974).

The remaining discussion on non thermal factors in thermoregulation will focus upon circadian rhythm, hydration, and age A more detailed discussion on non thermal control of sweating is presented in Section 1 3 2 3

1.2.2.1 Circadian Rhythm and body Temperature

It is well recognised that resting body temperature is not constant during a 24 hour period Metabolic heat production is constantly changing to meet the energy needs of an individual. Heat loss from the body adjusts according to heat production, with a lag in heat loss causing a change in body heat content and therefore T_{core}. Throughout a sedentary day, a circadian rhythm in body temperature may be observed Metabolic rate rises during the morning, remains steady throughout midday before falling to a minimal level during sleep Heat balance is achieved at each level of heat production, explaining the circadian variation in T_{core}. The difference in body temperature can be as much as 1 °C throughout the day, although considerable individual variation exists Regardless of physical activity, the daily variation in body heat content and T_{core} are unaffected, with values returning to their level on the diurnal curve after the cessation of activity (Webb, 1995).

1.2.2.2 Hydration and Fluid Homeostasis

During endurance based exercise and/or heat exposure individuals are advised to maintain euhydration, yet dehydration is unavoidable under such circumstances (Taylor and Cotter, 2006) As a result, decrements in performance are observed when sweating is the predominant mechanism for heat loss Thermal dehydration results in a

hyperosmotic, hypovolaemic condition, which has been suggested to initiate a decrease in heat loss responses (Sato, 1993). Hyperosmolality is proposed to increase the temperature threshold for both vasodilation and sweating whilst having no effect upon sensitivity, resulting in an increase in T_{core}. Decrements in hydration as small as 1-2 percent can affect the thermoregulatory system, reducing both skin blood flow and *SR* (Gleeson, 1998; Wendt *et al*, 2007). Since such levels of dehydration are commonly experienced during heat acclimation and exercise, the notion of fluid homeostasis contributing to optimal thermal adaptation must be considered Garrett *et al* (2004) observed increased exercise capacity and favourable fluid regulation responses with mild dehydration (~2%) following a controlled hyperthermia acclimation incorporating a euhydration versus dehydration cross over. Significant differences were observed between conditions for heart rate, cardiac output, strove volume, and performance on a standardised heat stress test, indicating the largely cardiovascular response involved in this mechanism of adaptation The level of dehydration found to elicit beneficial adaptation responses has be found to be of no determent to health or performance and may therefore require further consideration in both endurance training and heat acclimation practices (Taylor and Cotter, 2006)

1.2.2.3 Thermoregulation and Age

Internal body temperature is regulated within narrow limits, however the degree to which this is achieved is related to age In both extremes of chronological age, humans have a limited ability to respond to environmental extremes. Neonates need to be kept within a limited range of ambient temperatures to avoid hyper or hypothermia within the initial weeks of life. This limited ability of the body to protect itself against environmental extremes is suspected to result in part from the large surface area to mass ratio in newborns in comparison to adults The consequently large heat transfer to the environment in comparison to the relatively small mass of metabolically active tissue makes newborns susceptible to extreme ambient temperatures (Hey & Katz, 1970)

Elderly individuals demonstrated greater than 'normal' variation in core temperature (Exton-Smith, 1973). Decline in physical fitness with age is thought to contribute to the reduced efficiency of the circulatory system, resulting in 'age-related' decrements in thermoregulatory responses (Sato, 1993) This typically sedentary lifestyle also

contributes to a decrease in metabolic rate associated with age, explaining why older individuals prefer higher temperatures for comfort (Fanger, 1970,cited in Parsons, 2003) Decrements in circulatory function are largely responsible for the reduced ability to control heat dissipation to and from the core and skin surface for exchange with the environment. Under hot conditions, insufficient cardiac output compromises skin blood flow and therefore the ability to adequately dissipate heat from the body, resulting in hyperthermia Conversely, an aged-related decline in vasoconstriction reflexes cause a higher than required heat loss and reduced thermogenic response, lowering core body temperature and increasing the risk of hypothermia

1.2.3 Heat Acclimatisation

Acclimatisation and acclimation are terms commonly regarded as interchangeable, yet there are subtle differences in their meaning. Acclimatisation may be defined as the physiological adjustments induced by changes in the natural climate, reducing strain placed on an organism Acclimation refers to adjustments induced by artificial manipulation of climatic factors through experimentation or accelerated by exercise (Havenith, 1985; Mercer, 2001) Both processes result in an individual being in a state of acclimatisation, characterised by 'the attainment of an altered steady state' in order to minimise the energetic 'cost of living' (Lagerspetz, 2006, pp 1916) The adaptations resulting from acclimation are however fully reversibly over time following the termination of exposure. The concept of adaptation, decay following stimulus withdrawal, and its time course may be observed via the adaptation theory, illustrated in Figure 1 2

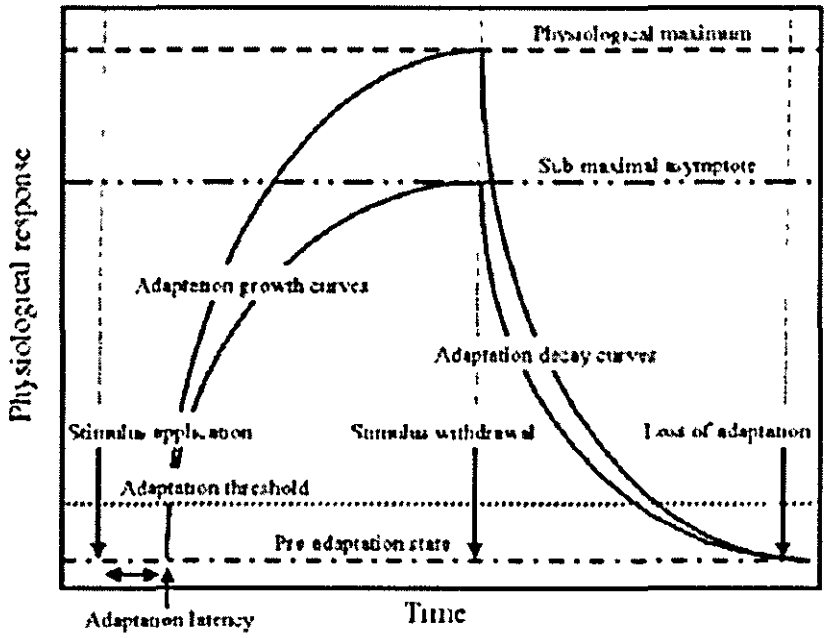


Figure 1.2. Adaptation theory (Reproduced from Taylor and Cotter, 2006)

The stimulus must exceed a specific threshold and disturb homeostasis to allow adaptation. The threshold is dependent upon the sensitivity of the thermoregulatory system and will shift with repeated exposure of sufficient magnitude and duration (Taylor and Cotter, 2006) The physiological adaptations associated with both acclimation and acclimatisation are well documented (Kuno, 1956; Fox *et al*, 1963, Nadel *et al*, 1974; Senay *et al*, 1976, Sato *et al.*, 1990, Lagerspetz, 2006, Shibasaki *et al*, 2006) Following a series of consecutive days heat exposure (minimum 3-7 days), a lower T_{sk} and T_{core} are observed (Buono *et al*, 1998), a lower heart rate during exercise, an increase in SR, a decrease in sweat onset and a reduction in subjective exertion and discomfort (Fox *et al*, 1963; Henane and Valatx, 1973; Mitchell *et al*, 1976, Shvartz *et al*, 1979, Nielsen *et al*, 1993, Sato *et al*, 1990) A number of acute physiological responses occur immediately upon heat exposure yet the latency period for adaptation varies greatly amongst individuals. The rate of response can be used to classify individuals into low, moderate, and high responders, with a low adaptation response observed in those with a high baseline adaptation (Taylor and Cotter, 2006)

The process of adaptation typically takes 1-2 weeks with a minimum of 60 minutes exposure per day (Havenith, 1985) The process of acclimation can be discriminated into several phases (Senay *et al* 1976; Aoyagi *et al*, 1997); upon initial exposure to heat, peripheral vasodilatation and an increase in sweating occur, with a subsequent

drop in blood pressure resulting from a decrease in venous return and cardiac filling pressure. An increase in heart rate is observed, however the heat load becomes too great and an increase in both T_{core} and T_{sk} results A progression towards cardiovascular stability marks the second stage, illustrated by an increase in blood volume and decrease in heart rate as both venous return and cardiac filling pressure return to normal. These physiological changes cause an increased cardiovascular fitness, in addition to a reduction in T_{core} and T_{sk} due to local 'training' of the sweat glands and a shift in central mechanisms increasing the SR. Finally, both T_{core} and T_{sk} achieve a new steady state due to an increased sweat sensitivity and capacity Essentially, heat acclimated individuals have a lower T_{core} threshold required for the onset of sweating. A higher sweat rate is exhibited for a given T_{core}, resulting in an increased cooling capacity (Nadel *et al*, 1974).

Givoni and Goldman (1973) developed a general model to describe the effects of working in the heat on both rectal temperature and heart rate. The model incorporates three important components of heat acclimation, firstly a decrease in initial rectal temperature; secondly a decrease in both rectal temperature and heart rate with work; and finally an increasing difference between acclimated and non-acclimated individuals as a function of the duration of work in the heat with regard to both responses. This model was validated against a series of data (Givoni and Goldman, 1973, Wyndham *et al*, 1954), fitting predicted and actual values very closely Criteria for the attainment of a state of acclimatisation are commonly based upon such models, the smaller the increase in T_{core} and heart rate on exposure the greater the degree of acclimation (Givoni and Goldman, 1973)

Research has highlighted changes in sweat gland function with acclimation resulting from peripheral modification (Knip, 1975). Sato *et al* (1990) observed morphological changes in eccrine sweat glands following heat acclimation Both in vivo and in vitro tests were performed on three male Patas monkeys; the typical reductions in $\overline{T}_{sk}$ and T_{re} were observed, in addition to an increase in sweat rate with the progression of acclimation (increase at 9 weeks and 9 months from baseline by 19% and 30% respectively) Sweat gland biopsy indicated an increase in sweat gland size ($p<0.05$) and

sweat production per unit of length of the secretory coil, achieving greater evaporative cooling In vivo sweating stimulated by methacholine (Mch) injection increased more than two-fold from pre-acclimation levels ($p<0.05$) These findings highlight the increased responsiveness of sweat glands to stimulation from the central nervous system (Sato *et al*, 1990). The use of Patas monkeys and a relatively small skin surface area does prevent these results from being truly representative of changes occurring in humans and over the whole body surface.

1.2.3.1 Acclimation Regimes

Adaptation theory (Figure 1.2) suggests that the capacity to attain a state of acclimation is dependent upon the intensity, duration and frequency of a stimulus and the genetic and phenotypic variability of an individual. This provides a simplistic means of comparing different thermal stimuli and the effectiveness of different regimes in achieving acclimation (Taylor and Cotter, 2006).

The most advanced heat adaptation is achieved through long-term 'natural' exposure (acclimatisation). Individuals native to hot countries respond to heat stress with lower skin blood flow and higher skin temperature than unacclimatised controls A lower, more efficient sweat rate is observed, reducing the wasteful loss of fluid accompanying short term acclimation Cardiovascular efficiency is improved through lower skin blood flow and heat gain is reduced through higher skin temperatures Importantly, the latter also increases cutaneous water vapour pressure, E_{max}, and evaporation. These changes are not evident following short term acclimation of only a few days or weeks (Taylor and Cotter, 2006) If artificially induced heat exposure with the absence of exercise is adopted, smaller increases in T_{core} are observed. This so called 'passive' acclimation technique is therefore considered less effective than all other methods of artificially induced heat adaptation (Taylor, 2000).

Passive heat acclimation techniques use exogenous (external) heat to illicit adaptation responses, with little contribution from metabolism Exogenous heat application can be achieved through a variety of methods, including water baths, water perfused suits, and thermal chambers. Passive acclimation is recognised to be less effective than other

methods of heat acclimation due to a lower and less rapid elevation in T_{core}. This is demonstrated by the development of a method by Fox *et al*, (1967) whereby T_{core} was rapidly elevated through exercise in the heat and then clamped during rest. This 'controlled-hyperthermia' technique uses both exogenous (external) and endogenous (internal) heat to evoke adaptation and is defined through a predetermined rise in T_{core} which is clamped for the duration of exposure. This demonstrates the need for exercise to elicit a greater and more rapid rise in T_{core} and produce greater heat adaptation than passive heat acclimation techniques.

It is commonly held that an increase in T_{core} provides the primary drive for the process of acclimation This may be observed in athletes who regularly increase T_{core} during training and competition, resulting in a high background adaptation (Robinson *et al*, 1943; Bass *et al*, 1955, Greenleaf, 1964; Piwonka *et al*., 1965). When athletes participate in acclimation regimes, physiologically they tend to show adaptation typical of individuals who have already been heat acclimated (Piwonka and Robinson, 1967). It therefore seems logical to assume that an acclimation regime which provides both exogenous and endogenous stimuli will produce the most efficient and complete result The exogenous stimulus will induce local 'training' of the sweat glands and contribute to an increase in T_{core} whilst the endogenous stimulus from exercise will provide the primary, sustained elevation in T_{core} The controlled-hyperthermia technique, typically modified using an exercise-rest protocol (Havenith and Middendorp, 1986), has repeatedly demonstrated a more complete heat adaptation than other methods Regimes involving exercise-induced heat acclimation are dependent upon the ability to maintain an elevation in T_{core} for an extended period This is achieved through increasing the exercise intensity upon repeated exposure, maintaining the same thermal load and subsequent T_{core} for the duration of the acclimation Thermal strain is known to decrease as acclimation develops, making techniques such as the 'constant work rate' regime a less effective example of the combined exercise and heat acclimation approach The same exercise intensity is used for the duration of acclimation with an observed decrease in T_{core}, heart rate, and perceived effort with repeated exposure (Henane and

Valatx, 1973; Mitchell *et al*, 1976; Shvartz *et al*, 1979, Nielsen *et al*, 1993, Taylor, 2000, Taylor and Cotter, 2006).

1.2.3.2 Hot-Dry and Hot-Wet Acclimation

In combination with the techniques of heat acclimation previously discussed, differing ambient conditions may be used, producing adaptation responses specific to those conditions 'Hot-wet' (humid) and 'hot-dry' conditions are typically used, with a high ambient temperature coupled with either a high or low relative humidity respectively. 'Adaptation specificity' may be observed under acclimation to a hot-wet climate, when a greater sweat response is produced compared to dry heat acclimation (Goldman *et al*, 1965; Shvartz *et al*, 1973). A high level of skin wettedness (discussed in detail in section 1.3.2.4) is required in 'hot-wet' conditions to maximise evaporative heat loss. The high sweat rate necessary to achieve this level of skin wettedness does however result in wasteful drippage with only a small increase in evaporative cooling (Winslow *et al*., 1936; Gagge, 1937; Candas *et al*, 1979a, 1979b, Candas, 1986). Participants acclimated in dry heat will not display as greater sweat response when placed in hot wet conditions compared to those acclimated in humid heat Conversely, upon adaptation to either hot-dry or hot-wet conditions, when subsequently exposed to a hot-dry climate, greater thermal strain is observed in those acclimated to hot-wet conditions (Shvartz *et al*, 1973). Similar findings were observed by Fox *et al* (1967), with subjects acclimated in hot-dry conditions displaying greater heat-acclimation compared to those exposed to hot-wet conditions. Upon post-acclimation exposure to hot-wet conditions, those acclimated in the hot-dry climate showed no greater capacity to sweat under those conditions, due to the high ambient vapour pressure limiting evaporative heat loss

1.2.4 Gender Differences

Considerable discrepancy surrounds the issue of sex differences in thermoregulation. Women are viewed to posses less effective thermoregulatory mechanisms, exhibiting a higher T_{core}, T_{sk} and heart rate and a lower SR compared to males (Fox *et al*, 1969b; Bittel and Hennane, 1975, Cunningham *et al*., 1978; Shapiro *et al*., 1980a, 1980b; Havenith *et al*., 1995; Havenith 2001a, 2001b) A higher setpoint of 0 1°C (Bittel & Henane, 1975) to 0.3°C (Fox *et al*, 1975, cited in Havenith, 1985, 2001) for sweat onset has been observed in females in comparison to males, suggesting a less efficient

sweating mechanism in females, allowing greater increases in T_{core} during heat exposure A similar phenomenon was found for T_{sk}, with females showing a 1-2°C higher set point than males (Hardy and Dubois, 1940; Fox *et al*, 1969) These factors may explain the delayed onset for sweating in females observed by some authors (Grucza *et al*, 1985). In contrast, similar T_{core} and *HR* values have been observed between males and females, suggesting more efficient sweating in females to maintain the same T_{core} as males This has further been suggested during humid heat exposure where women display a lower *SR* than males (Wyndham *et al*, 1965, Avellini *et al.*, 1980a; Shapiro *et al.*, 1980a) In an environment where high water vapour pressure restricts evaporative heat loss, the higher *SR* in males results in wasteful drippage The lower *SR* in females may therefore represent a greater sweating efficiency (Candas *et al*, 1982, Frye and Kamon, 1983). During dry heat exposure, some authors have observed similar *SR* between sexes (Shapiro *et al*, 1980a; Frye and Kamon, 1981) Much of this discrepancy between sexes relates to $\dot{V}O_{2\,max}$ and differences in workload between sexes (discussed in detail in section 1 1 4 2), highlighting the issue of matching males and females for cardiovascular fitness

Males and females posses different physical characteristics which may confound apparent differences in thermoregulation. There is much debate over matching or correcting groups of male and female subjects for direct comparison Many of the thermoregulatory differences that exist between groups of 'average' males and females may be due to morphological and physiological differences. It is however unclear as to whether or not these differences are simply due to factors such as fitness level and body composition or in fact due to differences in thermoregulatory function between sexes Large within group variation and a high degree of overlap between groups lead to the matching or correcting of subjects for fitness level and/or anthropometric results The original differences between male and female groups largely disappeared when matched, however discrepancies in data remain (Havenith, 1985) Some of the main issues surrounding gender differences in thermoregulation will be discussed in following sections.

1.2.4.1 Morphological Differences

Morphological differences between individuals are important in determining heat exchange with the environment and metabolic heat generation relating to body weight. Since body heat content is a product of body temperature and body heat capacity, body composition is important in thermoregulation (Sawka and Castellani, 2007) Body heat capacity relates to body mass and tissue specific heat, which will be constant for individuals of a similar body composition (Bligh and Johnson, 1973). Females are typically smaller, lighter, and posses a higher body fat percentage than males. The lower body mass of females provides a thermoregulatory advantage since a lower heat production and storage is observed in lighter individuals during exercise (Marino *et al*, 2000) The higher fat content in females should not impede heat loss in the heat since it is well perfused, however since the specific heat of fat is approximately half the value for lean body mass, individuals possessing the same body mass but higher body fat percent will warm up more rapidly at a given rate of storage (Bar-Or, 1969) Females are considered to be less effective in thermoregulation when exposed to high ambient temperatures and/or during exercise due to a higher T_{core} and lower *SR* (Fox *et al.*, 1969b; Bittel and Hennane, 1975, Cunningham *et al*, 1978, Shapiro *et al*, 1980a, 1980b; Frye and Kamon, 1981) However, females characteristically have a larger surface area to mass ratio than males, resulting in a greater area for cooling and therefore heat loss capacity. This is of great advantage in hot environments however represents a disadvantage in the cold, increasing the potential for hypothermia (Havenith, 1985)

1.2.4.2 Maximal Oxygen Uptake

An important point to consider when comparing males and females is whether to match them for $\dot{V}O_{2\ max}$, and in doing so taking an unrepresentative sample from one population, or compare 'average' individuals from each population If taking a mechanistic approach, one would match groups for $VO_{2\ max}$. If considering a more applied approach, 'average' individuals which are representative of the population would be used

Most studies adopt a protocol involving a work rate at a percentage of maximal oxygen uptake, using groups of males and females which are not matched for VO_{2max} (Avellini *et al.*, 1980a, 1980b) When exercising at the same relative work rate, little difference is observed in T_{core} between sexes however males demonstrate a significantly higher *SR* (Avellini *et al*, 1980a, 1980b) This may have caused artificial differences in thermoregulation between sexes, with females exhibiting a lower *SR* simply due to a lower absolute work rate (Bar-Or 1998, Havenith, 2001) When individuals who posses differing $VO_{2\,max}$ values work at the same relative work load ($\%\dot{V}O_{2\,max}$), the absolute oxygen uptake will be different. Individuals with a higher $VO_{2\,max}$ will have a higher absolute oxygen uptake and higher metabolic heat production during exercise To achieve thermal balance at steady state, the greater rate of heat production needs to be balanced by a greater heat loss, predominantly achieved through an increase in *SR* to achieve greater evaporative cooling (Gagnon *et al*, 2008). Differences in *SR* traditionally observed between sexes may therefore be caused by differences in metabolic heat production as opposed to differences in thermoregulation per se Some studies using groups of males and females matched for $VO_{2\,max}$, have indeed indicated an equal ability to tolerate heat exposure in males and females, despite differences in the functioning of thermoregulatory mechanisms (Avellini *et al.*, 1980a, Frye and Kamon, 1981; Grucza *et al*, 1985). Consideration of matching subjects for anthropometric and fitness parameters is therefore highly relevant for a direct comparison between sexes, since differences in thermoregulation have ceased to be significant upon matching or correction for such factors (Avellini *et al.*, 1980a;1980b, Frye and Kamon, 1981, 1983; Havenith and Van Middendorp, 1990, Havenith *et al.*, 1995)

1.2.4.3 Menstrual Cycle

It has long been recognised that the menstrual cycle causes changes in body temperature The menstrual cycle comprises of a follicular and a luteal phase, during which adjustments in the concentrations of estrogen and progesterone occur (Inoue *et al.*, 2005) T_{core} shows a rapid and sustained increase of between 0.5-0.75 °C at the time of ovulation This is likely to result from an increase in progesterone and decrease in estrogen release which occurs at this point in the menstrual cycle (Whitelaw, 1952, cited in Stitt, 1993; Charkoudian and Johnson, 2000). The characteristic variation in body

temperature observed over the menstrual cycle results from endocrine-related effects acting to modify both the resting T_{core} and the thresholds for sudomotor and vasomotor responses (Bonjour *et al.*, 1976, cited in Havenith, 1985, p10; Inoue *et al*, 2005) Some debate surrounds the extent to which the menstrual cycle affects thermoregulation, particularly during exercise and in comparison to men. In particular, controversy surrounds sweat regulation during menstruation, with the rate either being unaltered (Pivarnik *et al.*, 1992), or lower during the luteal phase (Kuwahara *et al*, 2002) In contrast, Garcia and colleagues (2006) observed an increase in total body sweat rate in women during the luteal phase, but no significant differences in heart rate, rectal temperature or $\overline{T}_{sk}$. This suggests that women are able to compensate for the higher resting T_{core} during the luteal phase during exercise through a higher SR Notably, the latter study emphasised fluid replacement during exercise compared to other studies which did not allow fluid replacement (Pivarnik *et al*, 1992), suggesting a possible role of hydration in equalising thermoregulation during differing phases of the menstrual cycle (Garcia *et al*, 2006). Inoue *et al* (2005) observed women to have a significantly higher T_{core} during the luteal phase compared to men but not during the follicular phase In agreement, Kolka *et al* (1987) observed no difference in T_{core} thresholds for sweating or vasodilatation during the follicular phase, however a higher threshold compared to men during the luteal phase Interestingly, Inoue *et al* (2005) observed no difference in T_{sk} between sexes regardless of the phase of the menstrual cycle. Since T_{sk} is recognised to affect sweating and cutaneous vasodilatation during heat exposure, this suggests no affect of regional differences in sweating and cutaneous vasodilatation responses to heat between sexes

Some authors have observed only a small degree of variation in temperature regulation due to the menstrual cycle, which was eliminated during exercise or passive heating (Kamon and Avellini, 1976; Shapiro *et al*, 1980, Horvath & Drinkwater, 1982; Frye *et al*, 1982) However, some of these studies were not primarily concerned with the menstrual cycle per se, but observed no differences in thermoregulation with menstruation as an additional finding Horvath and Drinkwater (1982) specifically addressed the issue of the influence of hormonal fluctuations during menstruation on thermoregulatory responses in women exercising in the heat. They concluded that the

physiological responses to exercise in the heat masked any effects of menstruation, regardless of any baseline differences. No significant differences in heart rate, total *SR* or T_{core} were present between ovulation, luteal or flow phases of the menstrual cycle Experiments were replicated across three different ambient conditions, finding no significant differences in thermoregulatory responses between phases of the menstrual cycle during exercise in the heat Under such circumstances the influence of menstrual cycle on thermoregulatory functioning has therefore been considered by some authors to be minimal in the presence of other inputs such as work and heat exposure (Havenith, 1985, p13).

1.3 Sweating

1.3.1 Human Sweat Glands

1.3.1.1 Classification and Distribution

Sweat glands were first discovered by Purkinjé in 1833. Since then it has been estimated there are 2-5 million sweat glands over the body, although no standard figure has been produced due to high levels of individual variation (Kuno, 1956; Szabo, 1962) There are three types of sweat gland on the human body apocrine, eccrine and apoeccrine sweat glands, of which eccrine will be the focus of this review. Apocrine sweat glands are located in restricted regions, primarily on the forehead, axilla, palmar, plantar, and pubic regions, always being associated with hair follicles. They are activated by psychological stimuli and produce smaller quantities of sweat than eccrine glands, however, their sweat is more viscous and is responsible for the odour produced in these regions (Sato *et al.*, 1989) Eccrine sweat glands have a thermoregulatory role and are distributed over the general skin surface of the body (Kuno, 1956, pp. 46-54; Montagna, 1962, pp 6, Sato *et al.*, 1989). They are greatest in number on the forehead, followed by fewer on the trunk and are least in number on the extremities (Kuno, 1956). They are stimulated largely by an increase in T_{core} and secrete sweat which evaporates from the surface of the skin to promote body cooling Their structure is a tubular epithelium, divided into the duct and secretory coil. The latter consists of a secretory coil and proximal duct. The distal portion of the duct connects the coil with the epidermis and stratum corneum, opening onto the surface of the skin (Sato *et al*, 1989) Finally,

apoeccrine glands are a hybrid between apocrine and eccrine sweat glands They develop during puberty from eccrine glands and are located only in the adult axilla Apoeccrine glands produce approximately ten times as much sweat as eccrine glands, consequently they are thought to contribute to axillary hyperhidrosis (Sato *et al* , 1989)

Eccrine sweat glands begin to develop at three months of embryonic growth on the ridge of the palms and soles, and over the rest of the body at approximately five months By the eighth month, the eccrine sweat glands have developed to resemble those of adults (Sato, 1977). Distribution of eccrine sweat gland density varies considerably between regions of the body. On the general body surface there appears to be no system of distribution unlike the linear arrangement of sweat glands on the palms and soles, opening along the cutaneous ridges (Krause, 1844 Cited in Kuno, 1956, pp 63) Cadaver studies indicate immense variation in sweat gland density between age and race, making a standard figure for distribution impractical (Kuno, 1956, pp 63) Kawahata (1939) found average total numbers of sweat glands from 11 Japanese cadavers to be 2.28±0 09 million This figure corresponds to results from Krause (1844, cited in Kuno, 1956) who found 1.6-2.1 million active sweat glands from Russian subjects, although racial differences are evident Values for regional sweat gland density were obtained from cadaver studies by Szabó (1962) As observed in Table 1 1, the greatest densities (± SE glands.cm^{-2}) were observed on the soles, forehead, and cheeks (320 ± 60) The lowest values were on the back, buttocks, lower legs, upper arms, and thighs.

Table 1 1 Regional variation in the density of sweat glands (Reproduced from Szabo, 1962 Pp 1)

Region	Number of Cases	Average Density per cm^2 ± S E Mean
Sole of foot	3	620 ± 120
Forehead	4	360 ± 50
Cheek	6	320 ± 60
Dorsum of the foot	3	250 ± 5
Forearm	5	225 ± 25
Abdomen + Groin	5	190 ± 5
Chest	4	175 ± 35
Back + Buttock	3	160 ± 30
Lower leg	5	150 ± 15
Upper arm	10	150 ± 20
Thigh	20	120 ± 10

Sweat gland activation in humans is not complete until approximately two years after birth From this point the number of active sweat glands does not alter with age There is however marked contrast in the regional distribution of sweat glands over the body between children and adults This may be explained by the variation in rate of growth of different areas of the body combined with the no change in the numbers of sweat glands The result is a variation in sweat gland density between body regions, appearing most marked on the extremities and torso, and less so on the head where comparatively less growth takes place (Kuno, 1956, pp. 71; Szabo, 1958, Weiner, 1964). Secretory activity of eccrine sweat glands varies considerably, but the presence of completely inactive sweat glands was first recognised by Sato (1934, cited in Kuno, 1956) and further demonstrated by Ogata (1935) Sweat glands are present in the human skin which show full morphological development yet no activity, leading to the subdivision of 1) active and 2) inactive glands (Ogata, 1935) When considering regional *SR* variation over the body, gland density alone may therefore not provide sufficient explanation, with factors such as gland sensitivity and output per gland being considered

1.3.1.2 Structure and Function

Eccrine sweat glands play a primarily thermoregulatory role on exposure to hot environments and during exercise. They produce a greater quantity of sweat which contains fewer organic substances compared to apocrine glands. Eccrine sweat glands

on the palmar and plantar surfaces tend to have a lower rate of secretion than that of the general body surface, profuse sweating is unlikely to occur. Sweat produced over the general body surface may become profuse, with sweat being very dilute and amounting to as much as 2-3 kg h^{-1} in some cases (Kuno, 1956, pp. 55)

There are distinct physiologic differences between apocrine and eccrine glands in addition to the differing methods of sudomotor transmission. (Neural control of sweat glands is discussed in more detail in section 1.3.2). Upon stimulation, the secretory coil produces a plasma-like precursor ultrafiltrate As the fluid passes along the sweat duct it becomes modified via active reabsorption of chloride and sodium A hypotonic sweat solution is formed which accumulates in the lumen of the sweat gland before reaching the skin surface. The resulting fluid is hypotonic compared with plasma, with values of sodium and chloride ranging from 10 to 70 mmol/L and 5 to 60 mmol/L respectively. Variations in the electrolyte content of sweat are determined by sweat rate, acclimation state, and dietary intake. The reabsorption process becomes of great importance during profuse sweating in maintaining homeostasis The eccrine sweat gland plays an additional role in the excretion of organic molecules, heavy metals, and macromolucules (Allan and Wilson, 1971; Saito, 1977; Robertshaw, 1977)

1.3.2 Control of Sweating

General thermoregulatory control mechanisms have previously been discussed (Section 1.1.2.). The current section will present control mechanisms specific to sweating, including both peripheral and central thermal inputs in addition to non thermal factors.

1.3.2.1 Central Control

It is well established that thermal sweating is controlled via a complex integration of sensory input from peripheral and deep thermosensors at thermoregulatory centres in the preoptic hypothalamus (Nielsen, 1938, Kuno, 1956; Montagana, 1962, Benzinger 1959, 1961; Sato, 1977, 1993). Neural signals descend from the brain to the spinal spinal tract, before synapsing with neurones at the lateral horn Sweat impulses continue along efferent cholinergic sympathetic neurons to secretory cells of eccrine sweat glands (Sargent, 1962, pp177). Acetylcholine is released at the sweat gland and

sweating is stimulated Such stimulation typically occurs when T_{sk} exceeds approximately 34°C and/or T_{core} exceeds approximately 37°C (Spearman, 1973). However, the presence of subthreshold sudomotor nerve impulses in the absence of sweating have been identified In cool ambient conditions, Ogawa (1970) observed synchronous pulsatile sweating in different regions of the body following the injection of sudorific agents. Ogawa and Bullard (1972) hypothesise that even in the absence of detectable sweating, sudomotor nerve impulses travel to the neuroglandular junction and it is the local conditions at the sweat gland that determined whether visible sweat is produced. Sweat measurements were made at three sites using resistance hygrometry, two of which were injected with pilocarpine (sudorific agent) and one being monitored for spontaneous sweating Participants were exposed to in the range of 19-45 5°C, showing a strong linear relationship between the frequency of synchronous expulsions and ambient temperature (r = 0 96), regardless of whether or not spontaneous sweating was present During abrupt changes in ambient temperature alterations in the frequency and amplitude of the drug-induced synchronous expulsions occured This was suggested to be reflexively initiated by thermoreceptors in the skin, which as supported by work from Belding and Hertig (1962) is the same mechanism responsible for generalised sweating (Belding and Hertig, 1962; Ogawa and Bullard, 1972) At temperatures greater than 20-22°c the results were indicative of sudomotor impulses continuously flowing form the central nervous system It was concluded that sudomotor impulses occur at cooler temperatures and stimulate sweat production, however, the amount of sweat that reaches the surface of the skin is dependent upon the amount reabsorbed along the sweat duct. Sweat is formulated in the lumen of the sweat gland where it accumulates before secretion onto the surface of the skin (Robertshaw, 1977). If the rate at which sweat is reabsorbed exceeds the rate of production then no sweat will appear on the skin (Lloyd, 1962; Ogawa and Bullard, 1972).

1.3.2.2 Peripheral Control

The role of T_{sk} in the regulation of sweat rate was initially introduced by Kuno (1956) He stated that if T_{sk} was primarily responsible for the stimulation of sweating then a sweating response would be observed with an increase in T_{sk} on exposure to high ambient temperatures. This however was not the case, implying that it is in fact T_{core}

that plays a greater role in the thermoregulatory process Since then researchers have explored the relationship between various T_{core} and T_{sk} with sweating, concluding a ratio of 9 1 for the relative contributions of internal and skin temperature to the thermal drive for sweating (McCook *et al* , 1965, Nadel *et al.*, 1971a; 1971b)

When addressing the influence of T_{sk} on *SR* it is important to differentiate between general T_{sk} affecting central control of sweating and local temperature affecting sweating at the glandular level The existence of peripheral inputs to the central control of sweating are demonstrated by changes in sweat rate under a constant T_{core} Local T_{sk} is known to affect local sweat gland activity (Gisolfi and Robinson, 1970, Ogawa, 1970, Ogawa and Asayama, 1986, Nadel *et al* , 1971; Sato, 1993), with the identification of particular threshold temperatures for the initiation of sweating (Randall, 1947) Randall demonstrated a threshold temperature for sweating which appeared to lie within a wide range of temperatures, above which sweating occurred and below which it did not This threshold value did vary greatly both within and between individuals, preventing an exact value being identified Using a colorimetric technique and an insulated chromel wire the subject's skin was heated between the range of 39.6-45.5°C. Marked differences in sweat spot size and number were observed compared with adjacent regions which may have varied from 10-15°C within a 5-10 millimetre distance. Such a distinctly localised response indicated the differential response of individual sweat glands to local heating. It should be noted that intense radiant heat of up to 45°C was used to provoke a sweat response which were not typical of temperatures that the skin is exposed to. Although useful for monitoring the development of sweating, the iodine method does not allow the sweat produced to be quantified Consequently the work by Randall does not allow the assessment of the relationship between local T_{sk} and the amount of sweat produced over a given surface area or by a single sweat gland.

The peripheral influence of localised heating on sweating may have possible mechanisms which are attributed to an increase in glandular sensitivity to neurotransmitter substances as a result of local heat application. Alternatively, metabolic processes may be directly affected within the secretory cells of the sweat glands, resulting in a peripheral modification of sweat rate Research conducted on the

effects of local heating on local sweat gland activity have produced T_{sk} of 38-45°C which are not typical temperatures that the skin is exposed to Ogawa (1970) studied this process using the physiological temperature range of 22-38°C in conjunction with injections of sudorific agents The results indicated that local heating may have very specific effects on the receptors of glandular cells due to increased local T_{sk} As a result the sweat threshold of cholinergic agents injected into subjects was affected but the local sweat threshold of adrenaline was unaffected The latter observation implies that local heating does not simply cause an increase in the metabolic activity of glandular cells, and suggests that only specific receptors may increase in sensitivity following local heating (Ogawa 1970) McIntyre *et al* (1968) proposed that for every nerve impulse released, local heating produced an increase in transmitter substance at the neuroglandular junction causing an increase in sweating This effect was observed by Ogawa and Asayama (1986) who used both localised heating and drug induced sweating with nerve blockades to assess the responsiveness of glandular cells to a transmitter substance and the affect of local temperature They concluded that a rise in local T_{sk} causes both an increase in the release of neurotransmitter per neural impulse, in addition to a heightened glandular sensitivity

1.3.2.3 Non-Thermal Factors

Modulation of sweating via non thermal factors is supported by many researchers (Nielsen, 1938, Benzinger, 1959, Van Beaumont and Bullard 1963, Gisolfi and Robinson, 1970; Shibasaki *et al*, 2006) Rate of sweating has been observed to be greater during exercise compared to rest, with rapid changes in *SR* preceding changes in T_{core} and T_{sk} (Robinson, 1962) The short latent period following initiation of exercise further suggest the existence of a non thermal input to sweating, termed by Gisolfi and Robinson (1970) as a 'work effect'.

Using sinusoidal exercise to distinguish between the many factors affecting sweating, Yamazaki and colleagues (1994) concluded that both thermal and non thermal factors affected the regulation of sweating during exercise During the 80 second test periods, T_{core} (here measured as oesophageal temperature) remained fairly constant, with *SR* showing a distinct sinusoidal pattern following the sinusoidal work. Changes in *SR*

preceded changes in T_{core}, indicating that sweating was directly influenced by non thermal factor changes prior to alterations in body temperature Extended sinusoidal work periods highlighted the decreasing role of non thermal factors in the modulation of sweating with time T_{core} contributed approximately 10, 15 and 50 percent to the change in SR during the 1.3, 4 and 8 minute test periods respectively during sinusoidal cycling. T_{sk} contributed approximately 10% of T_{core} during test periods, which is a contribution typically seen in thermoregulation (Nadel *et al*, 1971a; 1971b). Sinusoidal work is useful for assessing non thermal factors through separating out the different components of thermoregulation T_{core} remains relatively constant during steady-state exercise and oscillates with changes in work intensity, unlike the more rapid physiological responses resulting from non thermal factors

Van Beaumont and Bullard (1963) observed the occurrence of sweating within 1.5–2 seconds following the onset of exercise without an increase in T_{core}. A simultaneous increase in SR was observed on both the leg and resting forearm after initiation of maximal cycling, suggesting mediation via the CNS. Neither T_{sk} at a single site nor $\overline{T}_{sk}$ showed a detectable change at the onset of sweating, or any change in tympanic membrane or rectal temperature Gisolfi and Robinson (1970) similarly observed a sweat response within 1-2 seconds after work had begun when the subjects already had either an elevated T_{core} (38°C), or elevated T_{sk} (35 5°C), or both Such a rapid response cannot result from an increase in hypothalamic temperature since circulation time of blood is greater than that of the observed sweat response This evidence strongly suggests that during the initial stages of exercise, the central nervous system plays a considerable role in the augmentation of sweating. As exercise continues, thermal factors such as T_{core} take over predominant control (Van Beaumont and Bullard, 1963). The rapid increase in sweating in response to exercise is in fact transient, lasting for approximately 1-2 minutes. This is due to an increase in sympathetic nervous system activity and a possible reduction in parasympathetic tone. Following this initial rapid outbreak of sweating, the SR stabilises and is closely related to T_{core} (Stolwijk and Nadel, 1973).

Shibasaki and colleagues (Shibasaki *et al*, 2003a) tested the involvement of central command in the control of sweating via isometric handgrip exercises (IHG) followed by 2 minute ischaemia, either with or without partial neuromuscular blockade (PNB). The latter was used to enhance central command during the IHG *SR* was monitored via ventilated capsules on the non exercising forearm over a microdialysis membrane perfused with an acetylcholinesterase inhibitor (inhibits the cholinesterase enzyme from breaking down acetylcholine), increasing the level and duration of the acetylcholine, and at a second untreated site. Testing was conducted under three conditions, during normothermia, and mild and moderate heat stress. Isometric exercise is known to increase *SR* without alterations in core or skin temperature, indicating that non thermal factors are capable of modifying *SR*, for example central command. This was confirmed by Shibasaki's (2003) results, whereby IHG caused an increase in *SR* during both mild and moderate heat stress and also in normothermia at the neostigmine (acetylcholinesterase inhibitor) treated site, without increases in T_{core} or T_{sk}. The degree of the rise in *SR* was dependent on the thermal state of the subject The greatest increase in sweating occurred during IHG in mild heat stress conditions at a point at which the response of both sweating and T_{core} was small When comparing PNB and non PNB experiments, the increase in *SR* was greatest during the former condition, when central command was augmented. This suggests that central command possesses the ability to modulate sweating in the thermal conditions tested. These findings were confirmed by more recent work from Shibasaki and colleagues (2006) who concluded that a combination of both thermal and non thermal factors contribute to the control of human body temperature For example, in addition to central command, factors such as muscle metaboreceptor and mechanoreceptor stimulation may act to increase *SR* during exercise (Shibasaki *et al*, 2006) Another controversial factor in the control of sweating is baroreceptor unloading. Baroreceptors are highly sensitive to changes in blood volume and consequently detect decreases in pressure when blood volume decreases as a result of sweating and inadequate fluid intake It therefore seems feasible that *SR* may be modified by input from baroreceptor unloading These mechanisms and their potential contributions to the modification of sweating are not well understood and require further investigation.

1.3.2.4 Skin Wettedness and Evaporative Efficiency

The concept of skin wettedness was first introduced by Gagge (1937), using the dimensionless ratio of the surface area of skin covered by sweat which evaporates (A_e), and the total skin surface area of an individual (A_D). This ratio is derived from the calculation of the rate of evaporation from the skin, as expressed in equation (1 4) (Candas,1986):

$$E_{sk} = h_e \cdot \frac{A_e}{A_D} \cdot (P_{sk} - P_a) \qquad (1\ 4)$$

Where,

E_{sk}, evaporative loss from the skin (W m^{-2})

h_e, evaporative heat transfer coefficient (W m^{-2} kPa^{-1})

P_{sk}, saturated water vapour pressure at mean skin temperature (kPa)

P_a, partial pressure of water vapour in air (kPa)

When T_{sk} remains constant, two factors affect E_{sk}; firstly air velocity, causing a modification of the heat transfer coefficient h_e, and secondly, the ambient water vapour pressure (P_a), affecting the water vapour pressure gradient between the skin surface and the surrounding air (Candas *et al.*, 1979a) Under conditions where evaporation of sweat is necessary to maintain thermal balance, the adequate rate of evaporation necessary is referred to as the required evaporative rate (E_{req}) This value may not be attainable in hot, humid environments when the maximum rate of evaporation (E_{max}) is low, making control of body temperature difficult When sweat production surpasses E_{max} the entire surface of skin will become covered with sweat, equating to a skin wettedness of 100% $(w = 1)$ Skin wettedness may be calculated as the ratio between the actual $(E_{sk})$and maximal (E_{max}) rates of evaporation, as expressed in equation (1 5) (Candas, 1986):

$$w = \frac{E_{sk}}{E_{max}} \qquad (1.5)$$

The concept of sweating efficiency may be introduced when considering w in hot humid environments E_{sk} is restricted due to a decrease in the difference between the saturated water vapour pressure at the skin and the partial water vapour pressure of the environment $(P_{sk} - P_a)$. A high SR is required to achieve a high level of skin wettedness, causing some sweat to be 'wasted' through drippage (Winslow *et al.*, 1936; Gagge, 1937, Candas *et al.*, 1979a, 1979b, Candas, 1986) This phenomenon is commonly observed during heat acclimation, where an elevation in SR is misconceived to produce an equivalent increase in evaporative cooling. E_{max} is predominantly determined by the environment and not by the quantity of sweat produced SRs equating to an E_{req} in excess of E_{max} constitute an inefficient, wasteful fluid loss (Frye and Kamon, 1983; Taylor and Cotter, 2006) This inefficiency has traditionally been viewed as a failure of the thermoregulatory system

1.3.2.4.1 Hidromeiosis and Sweat Gland 'Fatigue'

It has commonly been observed that SRs decline following a number of hours of heat exposure This was initially attributed to 'fatigue' either of the controlling mechanisms or at the sweat gland itself (Sargent, 1962). One would therefore expect a more rapid and pronounced effect at a higher SR, which although observed, is more marked in humid environments (Gerking & Robinson, 1946) Under such conditions sweat drips from the skin surface, potentially making a decrease in SR an adaptive mechanism whereby central drive is reduced to conserve water (Candas, 1986, Taylor, 2000, Taylor and Cotter, 2006) The purpose and mechanisms underlying the decline in SR observed during prolonged heat exposure are however under much debate

Hidromeiosis refers to a reduction in SR associated with skin wettedness, describing a more dynamic and reversible phenomenon than so-called 'sweat gland fatigue' (Sargent, 1962) Peiss, Randall, and Hertzman (1956) observed a suppression of sweating in the hand during immersion in water or dilute saline (NaCl), but not when NaCl concentration exceeded 10 per cent. When exposed to such concentrations of NaCl water will no longer diffuse into the skin, preventing hidromeiosis (Buettner, 1959, cited in Sargent, 1962, pp. 197) Immersion in water would therefore produce greater epidermal swelling than in saline solution, causing decrements in sweating to occur over

a greater time constant in saline (Hertig *et al*, 1961). Hertig and colleagues used this method to estimate the relative humidity required to induce adequate epidermal hydration to cause hidromeiosis A solution of 15 per cent NaCl, equating to a *rh* of approximately 92 per cent, did not produce hidromeiosis, suggesting the relative humidity required to produce hidromeoisis lies somewhere between 92 and 100 per cent

The suggestion of epidermal swelling has lead to the suggestion of two possible mechanisms, firstly, cells lining the sweat duct may swell, causing obstruction. Secondly, diffusion of water into the epidermal layer dilutes the chemicals present in that environment, reducing the sensitivity of the receptors involved in sweating The idea of poral closure seems feasible since the whitening and wrinkling of the skin upon immersion of the hand suggests epidermal swelling, although less obvious over the general body surface where the epidermis is thinner (Kerslake, 1972). Either hypothesis seems feasible since hidromeiosis has been found to be a function of skin wettedness (Candas, 1986), accounting for the greater decline in *SR* under hot-wet compared to hot-dry conditions.

Hidromeiosis is a local phenomenon occurring only in regions where sweating is present and showing an exponential decline in *SR* towards zero (Edholm and Weiner,1981, cited in Parsons, 2003, pp44) This phenomenon is temporary, with local sweat gland function rapidly returning to previous levels once the skin is dried The explanation previously presented simply of blockage of the sweat duct fails to explain why the observed decline is exponential or why lesions from pressure build up in the secretory coil from poral obstruction have not been found (Candas, 1986, pp 82) A more complete explanation is that cellular fragments become stuck in the keratin ring at the mouth of the sweat duct due to epidermal swelling, forming a mechanical blockage (Montagna, 1962; O'Brien, 1974, cited in Kerslake, 1972, pp. 151). When skin is dried the keratin ring will shrink, allowing the cellular fragments to rapidly reach the skin surface The exponential nature of the decline in sweating is explained by the ability of liquid sweat to pass through a swollen keratin ring until the point at which it becomes blocked. The probability of a sweat duct becoming blocked is constant, making the rate of blockage proportional to the number of unobstructed glands. Sweating will therefore decrease exponentially towards zero (Kerslake, 1972). Contrary to this explanation,

mechanical occlusion of sweat pores has been deemed unlikely by Kittsteiner (1913, cited in Sargent, 1962, pp.187) since the secretory pressure of the sweat gland has been observed to be as high as 25 mmHg. Additionally, alterations in the keratin ring were not present in biopsy specimens in men exhibiting depressed *SRs* following 6 hours humid heat exposure (Dobson *et al* , 1958, cited in Sargent, 1962, pp. 187)

A linear correlation between initial *SR* and the level of decline during 6 hours heat (humid and dry) exposure in acclimated men has been demonstrated by Gerking and Robinson (1946). The effect of initial heat exposure is to produce an outburst of sweating, with the rate declining with longer exposure to levels which are possible to maintain. *SRs* of 2-3 $L.h^{-1}$ may be maintained for 30 minutes, with values falling to 1 5-2 0 and 0 5 $L\ h^{-1}$ after 4 and 24 hours respectively. Little hidromeiosis is present when initial *SRs* are approximately $700g\ h^{-1}$ or less in humid heat, equating to the maintainable level of sweating observed by other authors (Belding and Hatch, 1955, cited in Sargent, 1962, pp. 188-189) A decline in *SR* may therefore simply occur following an initial 'overshoot' which is a common phenomenon when an organism is placed under stress (Sargent, 1962, pp 182).

The 'overshoot' phenomenon fails to explain a depression in the rate of sweating independent of work load, irrespective of a continued increase in T_{core} , and showing a more pronounced effect at higher T_{sk} values (Gerking and Robinson, 1946; Ladell, 1957a, 1957b, 1959, cited in Sargent, 1962, pp. 166-173, MacDonald and Wyndam, 1950). Duration of exposure appears to be responsible for hidromeiosis, produced by a reduction in gland output rather than a change in the number of active glands. No change in sweat distribution of thermal sweating was observed with a starch-iodine technique, however sweat spot size was not considered, preventing quantification of the decrements in gland output (Thaysen and Schwartz, 1955, cited in Sargent, 1962, pp. 178)

Many authors have suggested 'sweat gland fatigue' as responsible for the depression of sweating over time, in addition to an increase in NaCl concentration observed with increasing *SRs* (Kittsteiner, 1913, cited in Sargent, 1962, Allan and Wilson, 1971). Secretory cells of the eccrine sweat glands produce a hypotonic sweat solution from

isotonic extracellular fluid, requiring osmotic work As *SR* increases, the sweat glands become fatigued and less osmotic work is performed, resulting in a sweat solution with a higher NaCl concentration (Kuno, 1956). However, upon a reduction in T_{sk} an immediate decrease in NaCl concentration may be observed, suggesting that sweat gland fatigue is unlikely (Van Heyningen, 1951, cited in Sargent, 1962, pp. 183). Furthermore, repeated heat exposure results in the absence of this increase in NaCl sweat concentration with time (Ladell, 1945b, cited in Sargent, 1962, pp 182) A considerable number of variables likely to influence NaCl sweat concentration are uncontrolled, *SR* has been correlated with NaCl concentration yet T_{sk}, work rate, acclimatization state, individual variation, and dietary intake, have not been investigated, making sweat gland fatigue still merely hypothetical (Robinson and Robinson, 1954, Kuno, 1956)

The mechanisms underlying hidromeiosis are still unclear, however if the ability to sweat actually declines then hidromeiosis will have important implications in the development of heat stroke. Conversely, if it constitutes a mechanism to achieve thermal equilibrium then it represents a beneficial adaptation (Ladell, 1955, cited in Sargent, 1962, pp 168).

1.3.3 Global and Regional Sweat Rates

Considerable research is available on global or 'whole body' sweating but there have been limited studies done on regional *SRs* Those that have investigated regional sweating show considerable variation in the data. This is highlighted by the work previously discussed by Randall (1947), who observed considerable variation in temperature thresholds for sweat gland activity both within and between individuals One problem with comparing much of the work conducted on regional *SRs* is that they relate to the thermal state of the body and so results may not be directly comparable between studies when differing thermal states are observed Data have tended to show great individual variation in regional *SRs* yet most research has only measured *SRs* in a small surface area in each body region, providing information specific to only a minimal area of skin. This is mainly a result of the use of capsules as the predominant

method of sweat collection which measure only a small surface area (3-10cm^{-2}) not necessarily representative of an entire region

Since the variation in thermally induced sweating fluctuates, simultaneous measurement across body regions is required to quantitatively assess the regional relationships. Some of the earliest work attempting to measure more than only a few sites was conducted by Kuno (1956, pp. 192-195) Adopting an absorbent method using blotting paper inside celluloid dishes (6 4 cm^2) attached to the skin, regional sweat production was calculated from the weight change of the absorbents across 20 loci Subjects were exposed to 39-40°C until sweating became profuse, at which time they were returned to a cool environment Notably, only four male and four females were tested and were all of Japanese origin, hence issues of ethnicity must be noted when considering these results for other populations. Regardless of ethnicity, variation in regional *SR* s over the body may be observed, with large differences in the quantity of sweat. The differences in *SR* between regions and variability in quantity are demonstrated in Kuno's results (Figure 1 3) Regardless of individual variation, common patterns of high and low sweat regions were apparent The forehead, neck, some regions of anterior and posterior trunk, lumber region and back of the head showed high sweat production Conversely, the lateral chest, extremities, internal femoral region, and axilla demonstrated low sweat production Such results have been confirmed by Weiner (1945) using 30 sites, and more recently by a number of authors (Cotter *et al* , 1995, Taylor *et al.*, 2006; Fogarty *et al* , 2007, Mochado-Moreira *et al* , 2008a; 2008b; 200c, Havenith *et al* , 2008). These studies consistently found *SRs* to be greatest on the torso, with a medial to lateral decrease in *SR* observed by Mochado-Moreira *et al* (2008a) and Havenith *et al* (2008), but not by Cotter *et al* (1995) In particular, the lumbar region of the posterior torso showed one of the greatest *SRs* over the body, in addition to the forehead. Lowest *SRs* were observed on the extremities, particularly on the ventral and plantar surfaces of the hands and feet respectively. Those data support that of Weiner (1945), who assigned values of 50, 25, and 25 percent to the trunk, legs, and head and upper extremities respectively for contributions to total sweat production.

Kuno stated that most individuals would fit into one of these categories depending on the body regions exhibiting the greatest *SRs* Although useful, Kuno's work exclusively involves Japanese subjects and therefore does not account for possible variation in *SRs* observed with ethnicity (Knip, 1975, Taylor 2006), although some differences in heat dissipation mechanisms may owe to long term acclimation (Bae *et al*, 2006)

Individual variation in regional *SRs* and indeed variation in the order of onset is highlighted by Hertzman (1957) Five nude subjects were exposed to temperatures ranging between 35-48°C, which were either kept constant or gradually increased over the measurement period. Following equilibration, body temperature, total *SR* and regional *SR* at 20 loci were measured for two hours, using sweat capsules *SR* was only measured on the left hand side of the body and only on a small *SA*, preventing generalisation of the data to the whole body. The small subject number (n=5) additionally prevents generalisation to the general population since considerable variation may be observed in sweat patterns and rates (Weiner, 1945; Kuno, 1956, Hertzman, 1957; Cotter *et al*, 1995; Taylor *et al*, 2006, Fogarty *et al*, 2007, Smith *et al*, 2007; Havenith et al, 2008, Machado-Moreira *et al*, 2008a; 2008b; 2008c) The results obtained indicated that although total *SR* and mean body temperature were fairly similar for four subjects, individual differences in regional *SR* at different T_a and differing orders of sweat onset amongst regions were observed Hertzman concluded that individuals may be categorised based on initial areas of sweat onset, similarly to that previously demonstrated by Kuno (1956)

Hertzman's (1957) findings are supported by his earlier work (Hertzman *et al*, 1953, cited in Stolwijk and Nadel, 1973) which indicated differing sweat rates in different areas of the body which are not initiated simultaneously for a particular level of central drive This indicates that both local thermal factors and body area are important peripheral modifiers of sweating Nadel *et al* (1971) confirmed these findings in their work using cycle ergometry at 80% peak power to stimulate sweating in an ambient temperature of 26°C and a relative humidity of 40% They observed that although there was slight individual variation, subjects showed a tendency to begin sweating on the chest, back and abdomen earlier than on the limbs The regions with the highest sweat rates were the upper back, chest, and thigh with values of 390-560, 360-560, and 250-

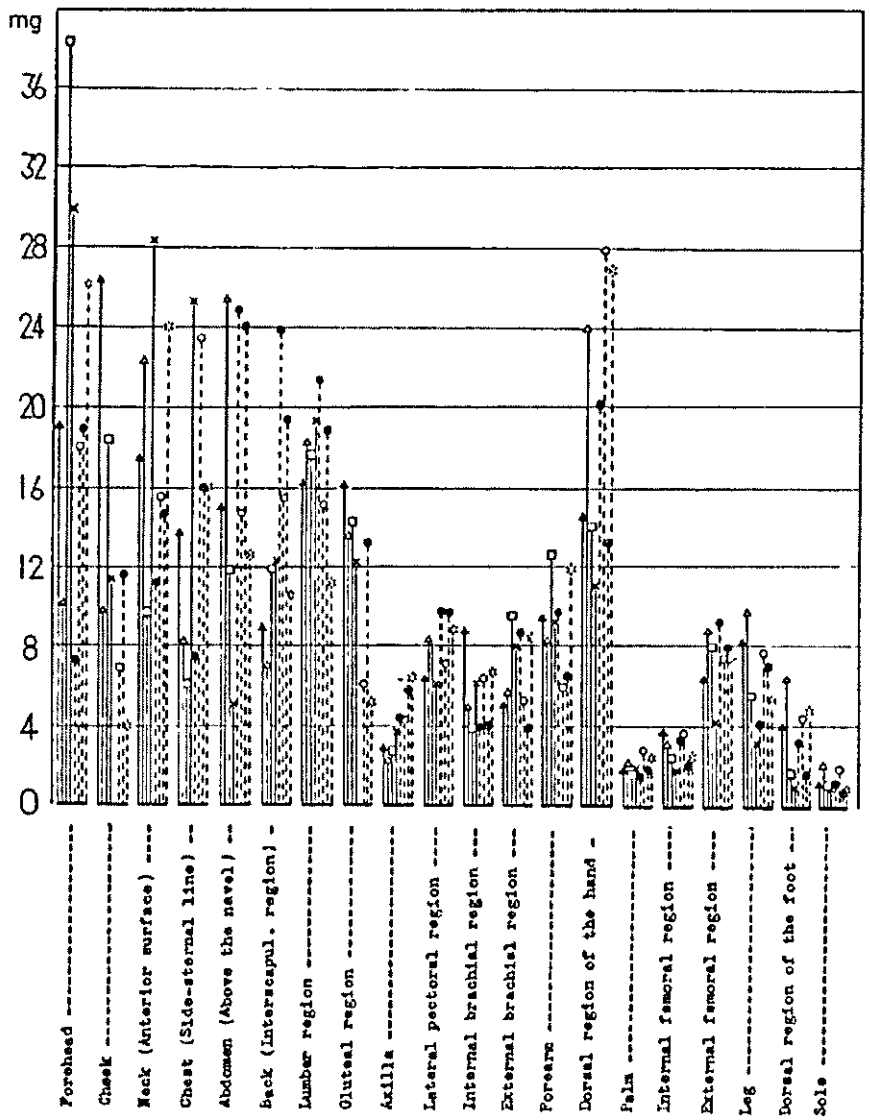


Figure 1.3. Regional relationship of the amount of sweat measured in 20 regions Each line represents one of the eight participants, four male and four female (reproduced from Kuno, 1956, pp 194)

According to a further set of comprehensive qualitative data involving 105 male Japanese subjects, Kuno (1956, pp. 195-204) categorised individuals based upon their patterns of sweat over the entire body Four classifications of sweat patterns were identified using a colorimetric method (methodology discussed in chapter 2)

- Uniform sweating
- Scant sweating on the upper limbs
- Scant sweating on the lower limbs
- Scant sweating on all limbs

560 g m^{-2} h^{-1} respectively These results do not concur with those found by Hertzman (1957) who observed some of the lowest *SRs* on the chest, with only 176 g m^{-2} h^{-1} The two experiments were conducted at two different temperatures and two differing thermal states i e. one involving intense exercise and the other at rest. This makes the direct comparison of such experiments very difficult due to the known differences in sweat rate according to ambient temperature, and the possibility of regional sweat rates changing with both exercise From Hertzman's work it was however concluded that each skin area has a characteristic internal temperature threshold, above which sweating is initiated. These findings are consistent with those of Hertzman *et al* (1953, cited in Nadel *et al*, 1971) and Kuno (1956, pp 192-195), with marked variations in both sweat patterns and rates being observed across the body. Nadel did not share the finding of a sweating pattern that developed caudally and ventrally, ascending up the body as the thermal demand increased. A major consideration in the comparison of these studies is the differing thermal loads applied to the subjects Those in Hertzman's study (1953) were exposed to high T_a (35-48°C) during rest compared to an exertion of 80% $VO_{2\,max}$ for 10-15 bouts of 10 minutes on a cycle ergometer in 26°C in the study by Nadel *et al* (1971) Hertzman (1957) did however observe general trends in his data which showed the increasing importance of the chest and abdomen with increasing ambient temperature, and the relative decrease in importance of the legs From this he suggested that the initial area of onset is on the calf and thighs, where sweating may remain limited until higher ambient temperatures are experienced. As the ambient temperature becomes higher, sweating becomes more uniform over the body, with sweat rates on the chest equalling those on the legs at as much as 400 g m^{-2} h^{-1} (Hertzman, 1957). This observation makes physiological sense with regard to maximising the effectiveness of heat loss via evaporation in high ambient temperatures

There are a number of reasons for the variations in regional sweat rates in individuals One result of the differences in the distribution of eccrine sweat gland density over the surface of the body is variation in regional sweat rates between individuals. This can be seen from the work conducted by Krause (1844, cited in Kuno, 1956) who provided numbers of sweat glands per surface area from cadaver studies His results show variation from values as high as approximately 249 and 114 sweat glands per square centimetre on the palm of the hand and the forehead respectively, to values as low as 38

sweat glands per centimetre square on the buttocks. More extensive research on cadavers of varying ages and races has illustrated that the immense individual variation observed in the distribution of sweat glands prevents a standard figure per unit area of skin for each region of the body being produced. It is estimated that there are between 2-5 million sweat glands over the surface of the body A number of researchers have noted that there are racial differences in the numbers of sweat glands distributed over the body. For example, from Japanese cadaver studies Kawahata (1939, cited in Kuno, 1956) calculated that there are 2 28 ±0.9 million sweat glands on the body. This finding is consistent with other literature (Szabó, 1962), however, slightly lower values of 1 6-2 1 million were observed in Russians (Krause, 1844, cited in Kuno 1956). Furthermore, it has long been recognised that the secretory activity of sweat glands varies between individual glands However, Sato (1934, cited in Kuno, 1956) made the observation that some glands appear to be fully morphologically developed but are incapable of secretion These glands are unresponsive to any form of stimulation and are consequently classified as inactive The distribution of these inactive sweat glands over the body may influence individual regional differences in sweat rate. Finally, the volume of sweat produced per gland has a considerable impact upon both the total sweat rate and the regional variation observed within and between individuals It has been estimated that the total volume achievable at a single time point of an individual glomerulus is approximately 40cc, although this can vary widely among individuals (Kodachi, 1942, cited in Kuno, 1956)

A typical characteristic of the secretion of sweat is the increase in the amount produced over time. The amount of sweat secreted becomes greater over time as subjects are repeatedly exposed to high ambient temperatures On occasions, when exposed to very high ambient temperatures, sweating from eccrine sweat glands may become profuse over the entire body, reaching levels of discharge in the region of 2-3 kilograms per hour (kg/h) or more. A point worthy of note is the seasonal differences which may be observed in sweating. It is known that individual's sweat more profusely in the summer months compared with other times of the year (Kuno, 1956) This is an important point to consider when conducting testing due to the comparison of data from different seasons producing inaccuracies due to the seasonal effect on SR.

1.3.4 Regional Sweat Rate Measurement

Methods for the measurement of perspiration from the human body with a measurable degree of accuracy date back as far as 1614 Sanctorius estimated insensible perspiration by weighing subjects on a balance sensitive to 0.1 gram (Sanctorius, 1614, cited in Kuno, 1956), a technique which is still employed for measuring total insensible weight loss A variety of techniques are now widely available for measuring both gross and regional *SR* s. The predominant methods used in regional *SR* research are:

- Sweat droplet analysis
- Ventilated or unventilated capsules
- Absorbents placed inside capsules
- Absorbents applied directly to the skin

Measuring *SR* distributions over the human body poses considerable methodological difficulties An overview of the main techniques and their limitations is therefore necessary and will be discussed in the following review.

1.3.4.1 Colorimetric Method

One of the earliest techniques widely used in regional *SR* measurement was Minor's colorimetric method (1927, cited in Kuno, 1956), both used and precisely documented by Kuno. This method attempted to qualitatively investigate regional sweat distributions over the whole body. Minor's method requires the skin to be uniformly painted with an iodine solution before heat exposure so that it appears homogenously yellow Once dry, starch is applied to the skin so that when sweating commences, the reaction of the iodine with the starch appears as dark spots on the white starch background As sweating progresses, the sweat spots increase both in size and number, and can be monitored via photographs and classified into stages The dye is removed from the skin once it begins to stream down the body. This colorimetric method is very simple for the observation of the development of sweating patterns over time. The technique does create considerable mess and does not allow the quantification of regional *SR* over time (Kuno, 1956; Ohhashi *et al*, 1998) In addition, assessment of the degree of sweating is often unreliable due to the humidity of the air surrounding the skin impacting heavily upon the colour reaction. Notably, the experiment has to be stopped as soon as sweating

becomes profuse due to dye streaming and preventing the observation of local sweating. It is therefore impractical for use in experiments using very high temperatures or those involving exercise It is however one of the few methods which allows investigation of the whole body at one time as opposed to the simultaneous measurement of small sections of skin.

Several improvements have been made to Minors colorimetric method involving the use of starch paper to create an imprint of the sweat drops appearing on the surface of the skin (Randall, 1946, cited in Kuno, 1956) This allowed for the observation of the size and distribution of sweat drops, however, all of the aforementioned disadvantages are still apparent in this method. Wada and Takagaki (1948, cited in Kuno, 1956) developed a colorimetric method involving the application of a solution over the body which prevented the evaporation of sweat from the surface of the skin As a result, the accuracy of the time onset of sweating and the degree of sweating is greatly improved It must be noted that problems may occur when photographing the sweat drops due to the oil causing reflections and that this method is only suitable for use on small areas of the body

1.3.4.2 Sweat Droplet Method

Sweating may be induced by injecting sudorific agents into the skin and an estimation of sweat rate calculated based on the size and number of sweat droplets produced Inoue *et al*, (1999) used this technique to investigate methylcholine-induced sweat gland density and sweat gland output pre and post acclimation. Petroleum jelly mixed with bromphenol blue was placed over the skin to dye the sweat blue and encourage beading of the sweat droplets An injection of acetyl-β-methylcholine in saline (0.9%) was administered under the skin and photographs were taken of each injected site at one minute intervals. An estimation of output per gland could be calculated based upon the measurement of each sweat droplet over time against a reference grid This technique provides a unique means of assessing individual sweat gland activity, however is impractical for use over large regions The laborious nature of the method and potential inaccuracy in producing an absolute measurement makes it unsuitable for large scale research. One distinct advantage of this method is its ability to isolate local sweat gland response, preventing involvement of the central nervous system. This is of particular

importance in investigating neural sweat control mechanisms and thermoregulation in spinal cord injury and paralysis research.

1.3.4.3 Capsule Techniques

The use of capsules has dominated sweat research in recent decades (Hertzman, 1957, Van Beaumont and Bullard, 1963; Ogawa and Bullard, 1972; Sawka *et al* , 1984, Aoki *et al* , 1995, Kondo *et al* , 1996, 1997) There are several varieties of capsule, ventilated, unventilated, and those containing absorbents. In all instances, capsules are glued or held in place on the skin during measurement The principle of the ventilated capsule technique is to calculate the water loss at the skin based upon the change in humidity and temperature of a gas passing through a sealed capsule at a known velocity (Nilsson, 1977). This allows a very accurate measure of *SR* in addition to enabling the continuous measurement over time Most studies use between three to five capsules, each placed on a single region of the body The calculated *SR* is then used as a general reference for each particular body area, yet it was until recently unclear if these samples were representative of the whole region (Havenith *et al* , 2008). Recently, researchers have attempted to improve the accuracy of their measurements by increasing the skin surface measured, Machado-Moreira *et al* , (2008a) used twelve capsules on the torso, ten capsules on the head (2008b), and Taylor et *al* , (2006) used five capsules on the feet. This has highlighted the inaccuracy of inferring small regional samples to larger body regions, also demonstrated by the use of technical absorbents applied directly to a large number of regions simultaneously on the torso by Havenith *et al* , (2008)

The method for calculating regional sweat loss in an unventilated capsule is based upon the weight change of a desiccant placed within a capsule (Nilsson, 1977) Hygroscopic salts were originally used and the water content determined via gravimetry (Robens *et al*., 2004), a technique sometimes used in the determination of the humidity of gas in ventilated capsules. Currently, the use of absorbent materials placed inside a sealed capsule is a more accepted method in unventilated capsules. Alternatively, the change in humidity of the air inside or leaving the capsule measured with dew point sensors may be used in the calculation of the *SR* The absorbent capsule technique uses a material which absorbs sweat produced on the skin surface inside the capsule and the weight change over time is used to calculate sweat rate.

The disadvantage of using any of the capsule techniques is the interference with the microclimate around the skin surface directly impacting upon the evaporative process (Nilsson, 1977; Gavhed and Havenith, 2003), causing either elevated humidity (absorbents) or reduced humidity (capsules) In particular, forced convection of moisture at the skin surface in ventilated capsules may artificially elevate the regional sweat rate. Conversely, this elevation in *SR* may potentially result in a lower skin temperature and a resultant decrease in *SR*. In addition, the ventilated technique requires the evaporation of all moisture within the capsule, with any water remaining on the surface of the skin reducing the local *SR* (Taylor and Buettner, 1953) The main disadvantage with using absorbents is the potential for moisture to become trapped on the surface of the skin. The resultant decline in evaporation and potential for hidromeiosis may cause a decrease in regional sweating (Gavhed and Havenith, 2004) However, a new technical absorbent may be able to prevent this from occurring (Fogarty *et al*, 2007; Smith *et al*, 2007, Havenith *et al*, 2008).

Capsule methods are extremely useful for the constant and accurate measurement of sweat rates, however, they are often impractical for use in experiments involving vigorous exercise due to the tubing required in ventilated techniques for example In addition, glued capsules in particular, cannot be attached and removed rapidly which may be required in some instances. Capsules have the distinct disadvantage of only covering an area of skin of approximately 2-9cm^2 which may not be representative of the region being measured The complexity of such techniques also makes the simultaneous measurement of a number of regions impractical

1.3.5 Conclusion

Following an extensive review of literature the following conclusions can be drawn

- Humans regulate their deep body (core) temperature around 37°C, fluctuating within narrow limits. This dictates that there is a heat balance between the human body and the environment, with heat gains and losses to and form the body being balanced
- The central controller for thermoregulation is located in the preoptic hypothalamus, receiving sensory input from peripheral and deep thermoreceptors, in addition to non thermal factors which modify thermoeffector responses.
- Local T_{sk} temperature affects sweating at the glandular level by increasing the release of neurotransmitter per neural impulse and heightens glandular sensitivity
- Exercise is an important non thermal factor in thermoregulation A reflex sweating mechanism stimulates sweating within seconds of beginning exercise with no change in T_{core} or T_{sk}.
- Women have been traditionally reported to thermoregulate less effectively than men during acute heat stress. More recently, gender differences in thermoregulation have been observed to largely be eliminated when participants were matched for physical parameters such as $VO_{2\,max}$, body mass to SA ratio, and body fat.
- Regional variation in sweat rate is well recognised over the body but has been measured on a limited number of sites and during differing thermal loads
- Regional sweat rate does not correlate strongly with sweat gland density. Factors such as neural sensitivity, glandular size, and output per gland must be considered
- Current quantitative methods of sweat measurement allow measurement on only a small surface area of skin, making simultaneous measurements over a large number of sites impractical. A new method for the measurement of regional sweat rates over the whole body is required

Chapter 2

Experimental Methodology

2 Chapter Summary

This chapter describes the experimental research methods used to investigate regional sweat rates in humans in the present series of studies The aim of this research is to provide detailed information on absolute regional sweat rates and the distribution over the whole body, using a modified absorbent technique A detailed description of the absorbent technique and the generic protocol for sweat mapping is provided in this chapter. Methods and procedures specific to single experiments are described where appropriate in other chapters.

2.1 Introduction

The very nature of sweat measurement involves some degree of interference with the very process being investigated. The methods reviewed (Chapter 1: 1 3 4) each have their advantages and disadvantages, sometimes producing discrepancies in the literature when comparing studies using different techniques The degree to which different methods may be compared is therefore questionable. Sweat rates are dependent upon the thermal state of the body, making comparison between studies difficult when differing thermal states are used. The predominant use of capsules in current thermophysiological research provides information on only small regions of skin, with inferences being made for regions as a whole. Sampling large areas of the body simultaneously would be too complex and time consuming to take reliable measurements using such a method To obtain detailed information on regional sweat rates over the entire body, a modified absorbent method of sweat collection has been developed. The method allows simultaneous measurement of large areas of skin over three progressive experiments, each covering approximately one third of the body. The same ambient conditions and experimental protocol were used during all experiments to allow a whole body sweat map to be developed

2.2 Experimental Design

Regional sweat rates were determined by applying absorbent material directly to the skin for a short, predefined, period of time. To minimise the effect of the pads on the overall thermal state of the body, the body sweat mapping was separated into three experiments 1) torso, 2) legs, and 3) arms, hands, buttocks, and feet. The testing sequence of body regions was randomised to prevent any order effect Each experiment involved steady state exercise at two relative workloads with a sweat measurement period at the end of each intensity. The same workload was maintained during the measurement period as had been performed during the preceding exercise intensity For statistical analysis the experiment was treated as a repeated measures design since a series of regional sweat rate measurements were made on each participant

A pre-experimental test session was used to perform a sub-maximal fitness test, measurement of skinfolds and collect anthropometric data. The latter was required for the calculation of absorbent pads specific in size to each participant.

2.2.1 Ethical clearance and Safety

The laboratory methods for all experiments undertaken are described under generic experimental protocols (G03-P13 thermoregulatory effects of warming in air, G04-P6 sweat measurement with the sweat absorption patches technique), which were approved by Loughborough University's ethical committee.

2.2.2 Informed Consent and Health Screen Questionnaire

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

2.2.3 Safety and Withdrawal Criteria

Due to the nature of the experiments, T_{core} values approaching 39°C were anticipated which could result in participants experiencing symptoms of heat stress. To prevent this from occurring, the following safety precautions were adopted:

- Participants were reminded that they could withdraw from the experiment at any time and without providing a reason
- Participants were frequently asked about their physical condition and were required to respond verbally.
- Participants were not permitted to leave the laboratory after the experiment until their heart rate had returned to resting level and they felt well enough to do so.

Strict withdrawal criteria were observed Experimental runs were terminated in any of the following instances

1. At the request of the participant.

2. At the discretion of the experimenter.

3. At completion of pre-decided duration for exposure.

4 If the participant's internal body temperature rose by 2 °C or increases to an absolute value of 39°C during heat exposure

5. If the average skin temperature rises above 38°C.

6. If participant heart rate rose above 85% of the age related predicted maximum for that participant (85% of [220-age] beats per minute) when dealing with healthy, untrained participants.

7. If participant heart rate rose above 93% of the age related predicted maximum for that participant (93% of [220-age] beats per minute) when dealing with athletes. (amendment to generic protocol G03-P13: thermoregulatory effects of warming in air, approved by the Loughborough University Sub-ethics committee)

2.2.4 Participant Recruitment

Participants were primarily recruited from the student and staff population at Loughborough University via email and poster advertisements. Suitability was

determined via a series of inclusion criteria specific to each study (described in each chapter) All participants were required to have no current injuries or medical conditions preventing them from exercising continuously for 60 minutes

2.2.5 Pilot Study

Extensive preliminary work was carried out to determine absorbent pad dimensions, pad locations, work rates, and work durations Considerable time was also spent determining the most effective method of pad application to different regions of the body. A thorough pilot study was conducted on ten participants, which may be referred to in a conference paper presented at the International Conference on Environmental Ergonomics (Smith *et al*, 2007) All the calculations for absorbent pad dimensions and methods of application are detailed thoroughly in this chapter.

2.3 Pre-Experimental Test Session

All participants were required to attend the Human Thermal Environments Laboratory a number of days prior to testing for a sub-maximal fitness test and anthropometric measurements. An explanation of the experimental procedure and aims were provided for all participants

2.3.1 Anthropometric Measurements

All participants were required to undergo anthropometric measurements. Stature was measured in centimetres (cm) using a stadiometer and weight was recorded in kilograms (kg) using an electronic scale (Mettler Toledo kcc150, Mettler Toledo, Leicester UK. Resolution 1g). Body dimension measurements were used in the calculation of absorbent pad sizes which allowed the individual production of pads for each participant. The anthropometric measurements and anatomical landmarks used in the pad calculations are based on guidelines by Lohman *et al.* (1988) in the 'Anthropometric Standardization Reference Manual'. As stated by Lohman *et al.* (1988), no single set of measurements will be sufficient for every study, therefore a number of measurements have been modified as required for the testing (Appendix B) A tape

measure was used for all body measurements and values were recorded to the nearest 0.1 centimetre

2.3.2 Skinfold Measurements

Skinfold measurements (SKF) were recorded from a number of sites on the right hand side of the body on male and female athletes and untrained male participants (Appendix B) using Holtain Tanner/Whitehouse skinfold calipers (Holtain Ltd. Crymych, Pembs, UK.). SKF are recognised as an indirect measure of adipose tissue and can be used to estimate total body fat The sum of measurements at a number of defined SKF sites were used to estimate total body density (Db) in grams per cubic centimetre (g cm^{-3}) and then used to derive total percentage body fat (%BF) based on certain established relationships. Of particular importance is the assumption that within each gender and according to fitness level the distribution of subcutaneous and internal fat is similar between individuals This has lead to the development of numerous population-specific equations which have been developed for relatively homogeneous populations, valid according to individuals having similar characteristics such as age, gender, ethnicity or fitness level (Heyward and Wagner, 2004). SKF measurements were taken at seven sites for male athletes: tricep, anterior suprailiac, abdomen, thigh, chest, midaxillary, and subscapular, defined by Jackson and Pollock (1978) for the calculation of Db. The formula used to calculate Db in male athletes is shown in equation (2.1):

$$Db = 1.112 - 0.00043499\left(\sum 7SKF\right) + 0\ 00000055\left(\sum 7SKF\right)^2 - 0\ 00028826 \cdot (age) \quad (2.1)$$

SKF were taken at four sites on female athletes; tricep, anterior suprailiac, abdomen, and thigh, defined by Jackson *et al* (1980) for the calculation of Db, using the formula in equation (2.2) :

$$Db = 1.096095 - 0.0006952 \cdot \left(\sum 4SKF\right) + 0\ 0000011\left(\sum 4SKF\right)^2 - 0\ 0000714\ (age) \quad (2\ 2)$$

As previously described, population-specific equations for the calculation of *BF* (%) are based upon individuals possessing similar characteristics Consequently, untrained healthy male participants required a different body density equation from trained males due to different levels of physical activity, and therefore a different subcutaneous and internal fat distribution (Heyward and Wagner, 2004). The *SKF* sites used, defined by Jackson and Pollock (1978), were the abdomen, thigh, and chest, which were used in the *Db* calculation illustrated in equation (2.3):

$$Db = 1.109380 - 0.000826\left(\sum 3SKF\right) + 0.0000016\left(\sum 3SKF\right)^2 - 0\ 0002574\ (age) \tag{2.3}$$

Following the calculation of *Db*, *BF* (%) was calculated using Siri's equation (Siri, 1956, cited in Heyward and Wagner, 2004), shown in equation (2.4).

$$BF(\%) = \left(\frac{4\ 95}{Db - 4\ 50}\right) \cdot 100 \tag{2 4}$$

The equation developed by Siri allows the calculation of *BF* (%) based upon constants for the density of different body tissue.

2.3.3 Sub-maximal Fitness Test

An estimation of aerobic fitness level, expressed as maximal oxygen uptake ($VO_{2\ max}$), was calculated from a sub-maximal fitness test based on the Åstrand-Ryhming method (American College of Sports Medicine, 2006). The sub-maximal fitness test was conducted on a treadmill ergometer (h/p/cosmos mercury 4 0, h/p/cosmos sports & medical gmbh, Nussdorf-Traunstein, Germany) under an ambient temperature of 18°C to prevent thermal stress Measurements of ambient temperature and humidity were taken using a Vaisala HMP35DGT sensor (Vaisala, Helsinki, Finland) and recorded at 1 minute intervals using an Eltek/Grant 10 bit, 1000 series squirrel data logger (Grant Instruments, Cambridge, England). Participants were fitted with a polar heart rate monitor and watch (Polar Electro Oy, Kempele, Finland) which recorded heart rate at 5 second intervals. The sub-maximal fitness test comprised of four exercise intensities

each lasting five minutes. Running speed was recorded for each intensity. The metabolic cost of running at each intensity was calculated in watts (W) for use in the prediction of $VO_{2\,max}$ based upon heart rate and workload. Equation (2 5), developed by Epstein *et al.* (1987), was used to calculate metabolic rate·

$$M_r = M_w - 0.5(1 - 0\,01\ L)\ (M_w - 15 \cdot L - 850) \qquad (2.5)$$

Where,

L external load (kg)

M_r metabolic cost of running (W)

M_w metabolic cost of walking (w), calculated using equation (2 6) developed by Pandolf *et al.* (1977)·

$$M_w = 1.5\ w_b + 2\,0(w_b + L) \cdot \left(\frac{L}{w_b}\right)^2 + \eta(w_b + L)\left[1.5 \cdot V^2 + 0.35 \cdot V \cdot G\right] \qquad (2\,6)$$

Where;

w_b body weight of subject (kg)

η terrain factor (η= 1.0 for treadmill)

V speed of walking (m s^{-1})

Using the calculated metabolic rate for each running intensity, $VO_{2\,max}$ was predicted for each participant in millilitres per kilogram per minute (ml kg^{-1} min^{-1}) using equation (2.7):

$$VO_2 = \frac{\left[\left(\frac{M_r}{350}\right) 1000\right]}{w_b} \qquad (2\,7)$$

The value of 350 Joules per minute (J min^{-1}) is based upon the energy utilized per litre (L) of oxygen consumed (American College of Sports Medicine, 2006). The heart rate for each level was plotted against predicted VO_2 values using SPSS (Statistical Package for the Social Sciences, version 16 0, Chicago. USA) for each respective intensity. A

best fit line was applied and extended to the value of the age predicted maximum heart rate (220-age) allowing $VO_{2\,max}$ to be predicted from the x-axis.

2.4 Experimental Preparation

Absorbent pads were individually produced for each participant based upon the pre-test anthropometric measurements The size and positioning of the pads was developed using a heuristic technique based on a ratio system of anatomical landmark measurements to the pad length for a body region (see appendix B for all calculations) All pads were 'mocked up' as paper templates before being traced onto absorbent material (Product 2164-Laminated Airlaid, Tech Absorbents, Grimsby, UK) and cut out. A total of 70 regions were measured on male participants and 78 on females A greater number of pads were used on the female anterior upper torso compared to the males to allow full coverage of the breasts. Absorbent pads were applied to the torso, arms, legs and ankles (male: 48 pads, female. 56 pads). Cotton gloves (100% cotton knit material stitched gloves, The Healthy House Ltd, Stroud, Glos., UK) were applied to the hands (14 regions) covering the palms, dorsal hand and fingers A combination of absorbent pads and cotton socks (100% cotton material, Universal Textiles, Leicester, UK) were applied to the feet (8 regions) covering the sole and the top of the foot respectively All participants wore a standardised reference forehead pad attached to a sports headband for the duration of each pad application period. The locations of all pads for male and female participants are illustrated in Figure 2.1 and Figure 2 2 respectively, with the corresponding labels outlined in Table 2 1:

Table 2.1 Labels for male and female absorbent pad locations

1	shoulders	19	anterior medial lower leg
2	lateral upper chest	20	posterior lower leg
3	medial upper chest	21	anterior upper arm
4	lateral mid anterior torso	22	posterior upper arm
5	medial mid anterior torso	23	anterior lower arm
6	sides	24	posterior lower arm
7	lower anterior torso	25	thumbs
8	lateral posterior upper torso	26	fingers
9	medial posterior upper torso	27	palms
10	lat pos M-U	28	dorsal hand
11	lat pos M-L	29	buttocks
12	centre pos mid	30	sole
13	posterior lower torso	31	dorsal foot
14	anterior upper leg	32	toes
15	medial upper leg	33	heel
16	posterior upper leg	34	med ankles
17	lateral upper leg	35	lat ankles
18	anterior lateral lower leg		

a	upper chest
b	medial upper bra
c	lateral upper bra
d	medial lower bra
e	lateral lower bra
f	bra triangle

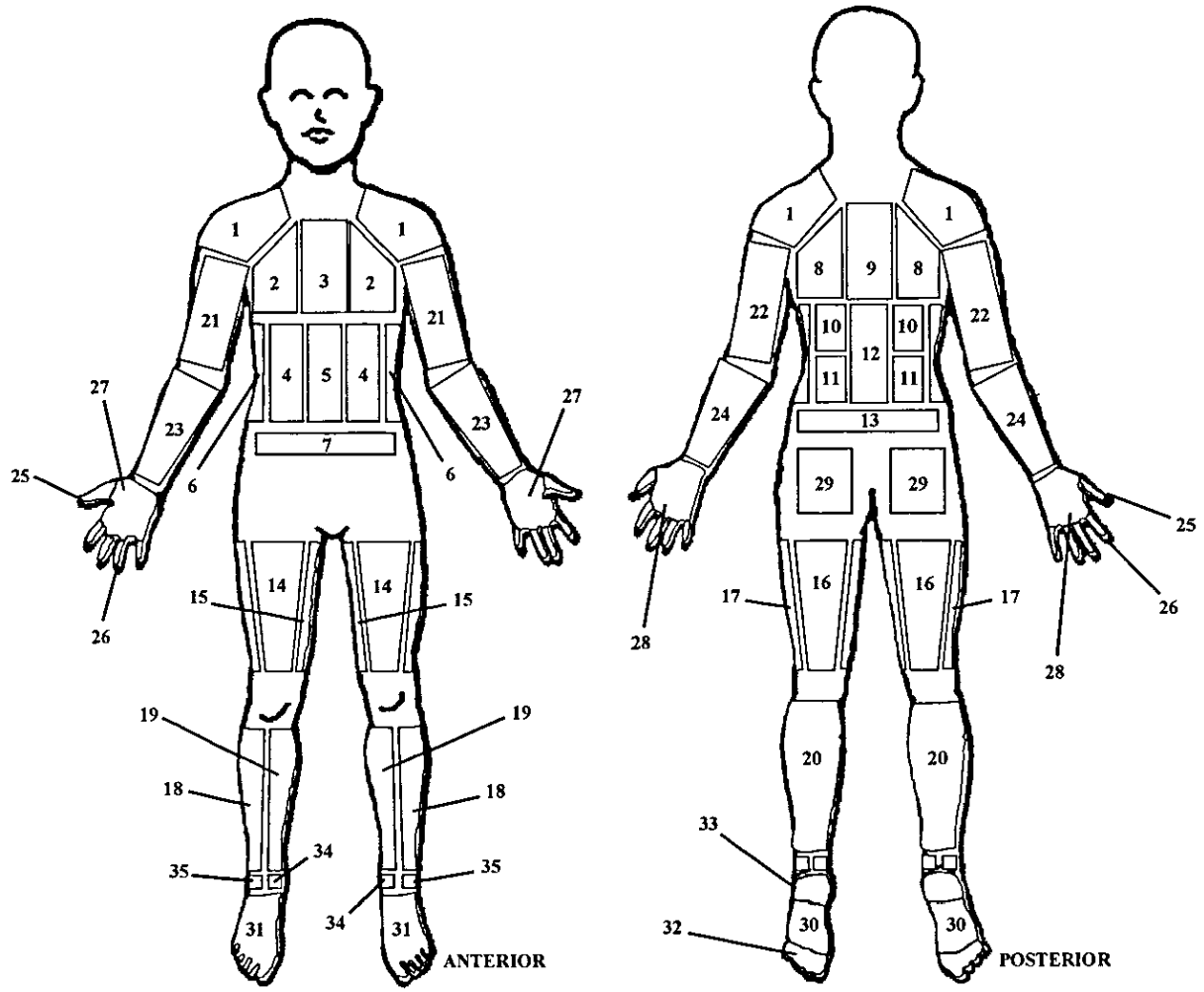


Figure 2.1. Location of absorbent pads for male participants

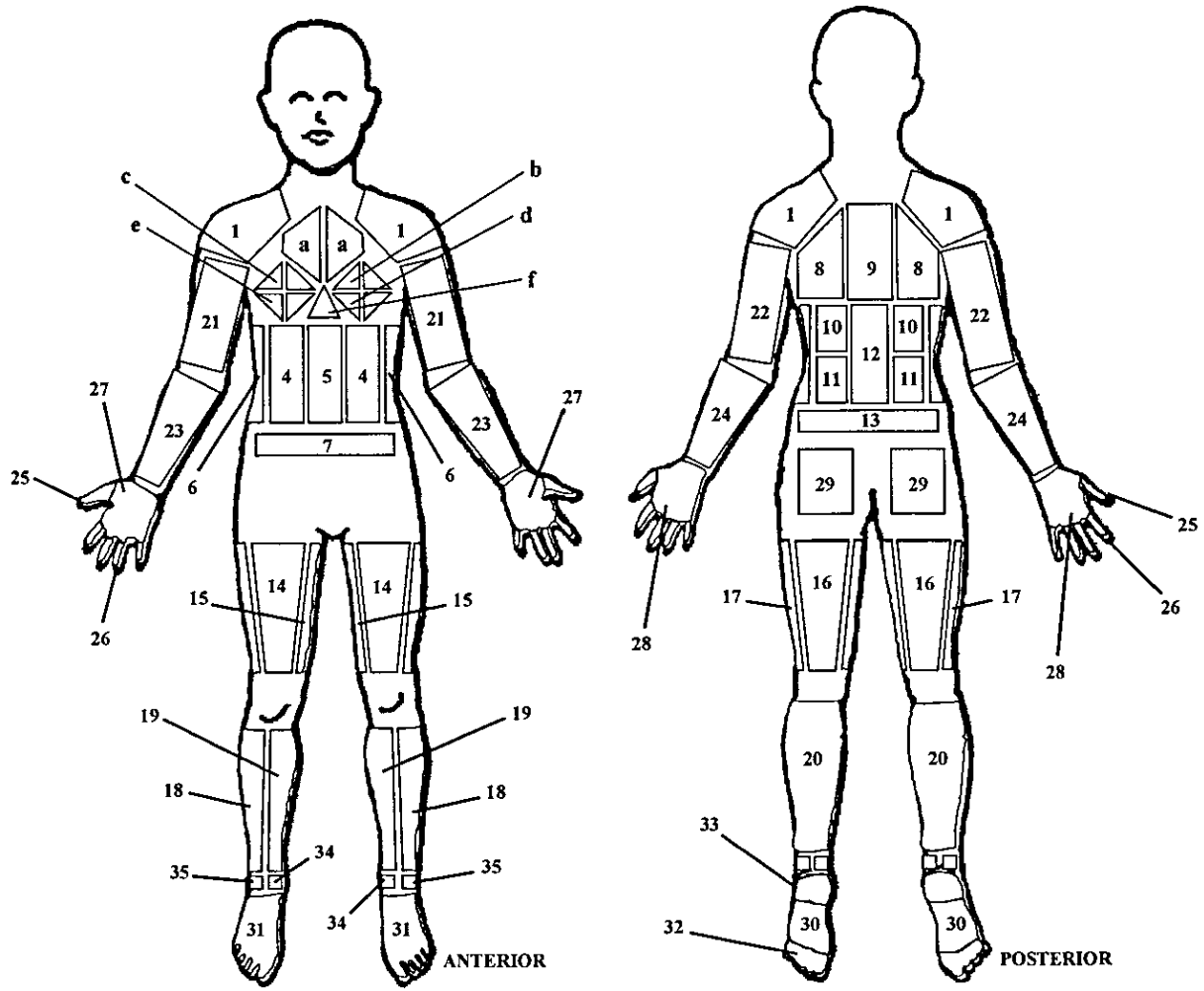


Figure 2.2. Location of absorbent pads for female participants

As previously stated, the body sweat mapping was separated into three experiments to minimise the effect of the pads on the body's thermal state Descriptions of pad application during each experiment are outlined below.

2.4.1 Absorbent Pads of the Torso

Both male and female participants had absorbent pads placed on both the anterior and posterior torso, in addition to one pad on both the left and right lateral region (sides) along the mid-axillary line. The anterior and posterior torso was divided into upper, mid, and lower regions which were further subdivided to define each pad location (Figure 2 3, A) For example, the anterior mid region was subdivided into three equal sections; right, mid and left. Male and female participants had participants had a total of 20 and 28 pads covering the torso respectively

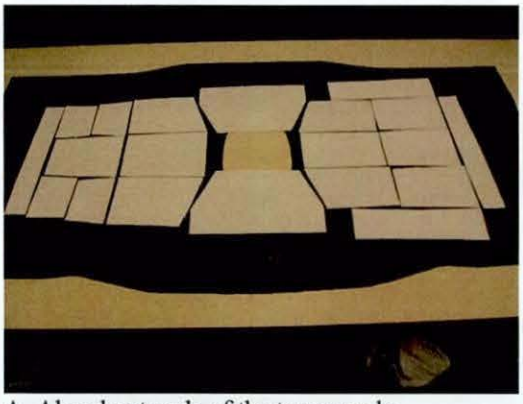
2.4.2 Absorbent Pads of the Legs

Unlike the torso, male and female participants were attached with an identical pad layout on the legs The upper leg was divided into four equal sections, anterior, posterior, medial, and lateral The lower leg was divided into two equal size anterior pads and one larger pad covering the posterior (Figure 2 3, C)

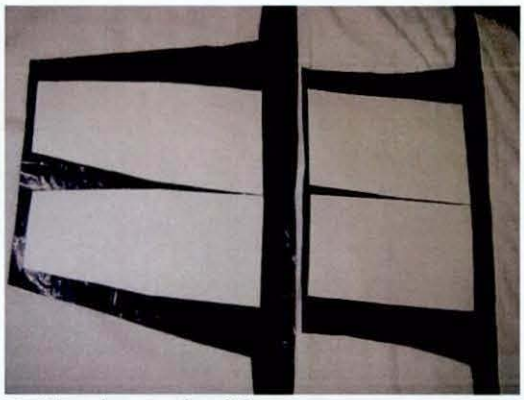
2.4.3 Absorbent Pads of the Arms, Hands, Buttocks, and Feet

Male and female participants had an identical pad layout for the arms, hands, buttocks, and feet. The arms were divided into upper and lower regions and further subdivided into anterior and posterior, producing two equal pads for both the upper and lower arm (Figure 2 3, B) Pads were produced for both the right and left buttock. The hands and dorsal regions of the feet were difficult areas for pad application and for maintaining their position during physical activity Following a number of trials, it was decided to use one hundred percent cotton material for sweat collection on both the hands and feet. The simplest method for its application was to use cotton socks and gloves To prevent moisture wicking and the migration of sweat between different regions on the hand, small incisions were made at the base of each finger and thumb using a scalpel. To maximise the detail of the regional sweat rate date collected on the plantar surface of the

foot, it was decided to produce absorbent pads to place inside the base of the cotton socks. One absorbent pad was produced for each foot, specific in shape to the feet of each participant (Figure 2.3, D). The pad was divided into the heel, mid-sole, and toes, based upon the start points of the first and fifth toes and the position of the medial and lateral malleoli. Using a scalpel, the absorbent material was cut away from its plastic backing along the borders of the three marked regions. A width of one centimetre of absorbent material was removed to separate the regions and to prevent the migration of sweat. The top of the cotton sock was used to collect sweat on the dorsal surface of the foot.



A. Absorbent pads of the torso: male



B. Absorbent pads of the arms

C. Absorbent pads of the legs

D. Absorbent pads of the sole, heel and toes

Figure 2.3. Absorbent pads and plastic sheeting of the (A) torso, (B) arms, (C) legs, and (D) feet.

2.4.4 Weighing of Absorbent Pads

Airtight zip-lock bags were individually labelled for each pad and weighed using electronic scales (Sartorius YACOILA, Sartorius AG, Goettingen, Germany. Resolution 0.01g). The weight of each bag was recorded and the corresponding pad was placed inside and weighed before and after application. All pads were stored inside their individually labelled airtight bags until testing.

2.4.5 Weighing of Cotton Material

Unlike the absorbent pads, the individual sections of the gloves and socks to be measured could not be weighed prior to testing. The cotton material could not be separated for weighing and then applied to the skin as its structure would be lost. Specific sections of the socks and gloves were cut up immediately following sweat collection and placed in individually labelled airtight bags. The wet weight of each individual section was recorded and the material was then removed from its bag. Each section was then placed in a thermal chamber at 30°C, 50% *RH* for 24 hours to allow the material to dry out. The sections of material from the hands and feet were removed from the thermal chamber and re-weighed inside their corresponding airtight bags to establish the dry weight.

2.4.6 Absorbent Pad Application

All pads were attached to customised plastic sheeting using double-sided tape to allow simple and rapid application during testing. The customised plastic sheeting was individually produced for each subject and was based on the anthropometric measurements taken in the pre-test session (see Appendix B for all calculations). The absorbent pads used for the breasts in the female testing were attached to a sports bra of appropriate size for each participant using double-sided tape. Female participants were required to wear this 'purpose built' sports bra during the sweat collection periods in the torso sweat mapping. The absorbent pads covering the heel, mid-sole and toes were attached to the inside sole of a pair of cotton socks. Participants were required to wear the cotton socks during test periods with their feet placed carefully on top of the absorbent pads. To prevent sweat passing down the body from the axilla and legs from areas which were not covered by pads, absorbent material was applied under each axilla and over each knee (patella). These pads were discarded after testing.

Application of the torso pads was done via a single piece of plastic sheeting. A hole was cut in the top of the plastic sheeting to allow it to be placed over the participant's head and then secured in place using tape to attach both sides together. A stretch zip t-shirt was placed over the head of the participant and zipped on both sides to ensure the absorbent pads were pressed against the skin and held in position (Figure 2.4). The same method of application was used for pads over other areas of the body. The arm

pads were applied using two separate customised plastic sheets on each arm, one for the upper pads and one for the lower pads. The participant was required to stand in the anatomical position to identify the anterior and posterior regions of the arms. The plastic sheeting was secured in place using tape and kept in position using a stretch zip t shirt. The leg pads were attached using two separate customised plastic sheets for the upper and lower pads on each leg. The pads were secured in place with tape down the side of the leg between the anterior and lateral pads on the upper leg, and between the anterior lateral pad and the posterior pad on the lower leg. Participants wore a pair of zip lycra running leggings which were zipped down each side to keep the pads in position (Figure 2.4). The cotton socks, which contained plantar foot pads, were covered using latex 'foot covers' (Triboard Decathlon, Lille, France) which were taped in place over the foot to prevent the evaporation of sweat from the socks. Similarly, the cotton gloves were covered with skin tight latex laboratory gloves. This was to ensure the cotton was pressed against the skin and that no sweat would evaporate from the material during the sweat collection period.

A. Application of torso pads

B. Application of zip t-shirt

C. Application of leg pads

D. Application of zip trousers

Figure 2.4. Application of absorbent pads, plastic sheeting and stretch zip clothing of the (A) torso and (B) legs.

2.5 Generic Sweat Mapping Protocol

2.5.1 Experimental Set Up

All experiments were conducted at 25°C in a climate controlled laboratory in the Human Thermal Environments Laboratory, Loughborough University. All sweat Mapping experiments were conducted on a treadmill (h/p/cosmos mercury 4.0 h/p/cosmos sports & medical gmbh, Nussdorf-Traunstein, Germany), with three 50cm diameter fans (JS Humidifiers plc, Littlehamption, UK) arranged in a vertical line (Figure 2.5). This enabled an equal distribution of wind over the height of the body, set at an air velocity of 2.0 $m.s^{-1}$. Regular calibration of air velocity was performed using a hot wire anemometer (model TSI Alnor 8455. TSI Instruments Ltd, High Wycombe, UK. Range 0.125-50 $m.s^{-1}$.). Data output was recorded on a Eltek/Grant 10 bit, 1000 series squirrel data logger (Grant Instruments, Cambridge, England) at 30 second intervals.

Figure 2.5. Photographs of the experimental set up for sweat mapping.

2.5.2 Pre-test preparation

Participants were advised to consume 20 $ml.kg^{-1}$ body weight of water during the 2 hours prior to testing in order to maintain euhydration. They were also instructed to abstain from caffeine and food consumption during this period. In addition they were required to abstain from high intensity physical activity and alcohol 24 hours prior to testing.

2.5.3 Generic Experimental Outline

Body weight and sublingual temperature were recorded at the beginning and end of each experimental session Measurements of ambient temperature and humidity were taken using a Vaisala HMP35DGT sensor (Vaisala, Helsinki, Finland) and recorded at one minute intervals using an Eltek/Grant 10 bit, 1000 series squirrel data logger (Grant Instruments, Cambridge, England). Participants were provided with clothing (see 2.5.4. Clothing) and a heart rate monitor and watch (Polar Electro Oy, Kempele, Finland) for use during testing All sweat mapping experiments consisted of two exercise intensities based upon a fixed heart rate A low exercise intensity of 125-135 bpm was performed for 30 minutes, followed by a high exercise intensity in the range of 150-160 bpm for 20 minutes (equivalent to 55 and 75 percent $VO_{2\ max}$) The first five minutes of the low intensity was used to allow the participant to warm up and determine a constant running speed Absorbent pads were applied to nude, towelled dry skin for five minute periods at 30 and 60 minutes, during which the exercise level of the proceeding period was continued Infra red images were taken at the beginning and end of the experiment, and prior to and following each pad application, as described in section 2.5 5.

2.5.4 Clothing

Clothing for all experiments was standardised between participants. On arrival to the laboratory participants were instructed to change into 'test short' (Quechua, Decathlon, France) and a 'test t-shirt' (Quechua Novadry, Decathlon, France) They wore their own shoes, socks, and in the case of females, sports bra, except during sweat collect periods when a sports bra was provided for the application of absorbent pads. During sweat collection periods all participants wore a custom made stretchy 'zip-shirt' and stretchy 'zip trousers' (Quechua, Decathlon, France) depending on the body region being tested, which assisted in holding the absorbent pads against the skin with a low, uniform pressure.

2.5.5 Infra Red Imaging

Infra red thermal image photographs (Thermacam B2, FLIR Systems Ltd , West Malling, Kent, UK Thermal sensitivity 0.1°C, accuracy ±2°C) were taken to determine

regional skin temperature (T_{sk}) Sweat was wiped from the skin using a towel to prevent environmental infra-red reflecting off the sweat on the skin surface Baseline infra red images were taken at the beginning of each experiment. Further images were taken prior to each pad application and immediately after removal to assess the affect of the absorbent material upon skin temperature. The images were later analysed (Thermacam Reporter Pro, FLIR Systems Ltd , West Malling, Kent, UK) to determine regional and mean skin temperatures (see section 2 6 4)

2.5.6 Fluid Consumption

Water was provided in a sports drinks bottle which was weighed at the start and end of each experiment. Participants could drink freely through out the experiment, however were required to inform the experimenter when consuming water if an ingestible telemetry pill had been swallowed.

2.5.7 Core Temperature Measurement

T_{core} was measured in two ways during testing. Firstly, sublingual temperature was measured prior to and at the end of each experimental session A thermometer was placed sublingually with the mouth closed for five minutes before a measurement was recorded Secondly, an ingestible temperature pill was used during one of the three body mapping experiments for all participants A Vitalsense Integrated Physiological Monitoring System (Mini Mitter Company, Inc. Bend, Oregon, USA) was used, supplementing the sublingual temperatures taken. The system consisted of a Vitalsense monitor, Vitalsense Application software (version 1.12), an RS-232 download cable, and CorTemp™ ingestible 'temperature pills'. The use of this system has been approved by the Loughborough University Ethical Advisory Committee (Generic Protocol· G03-P4) All participants read an information leaflet before completing an informed consent from (Appendix A) and health screen questionnaire (Appendix A) specific for radio pill use. Each participant consumed a 'temperature pill' for one of the three sweat mapping experiments unless they were not suitable to do so, as detailed by the health screen questionnaire. Each experiment was identical with exception only to the placement location of absorbent pads and therefore did not warrant the repeated consumption of temperature pills by each participant. Each 'temperature pill' was activated using the

Vitalsense monitor and assigned a unique code before being administered to the participant with instructions for consumption The 'temperature pill' was swallowed five hours before the experimental session and a wristband was worn in the interest of safety to identify each participant as having taken an MRI incompatible device.

On arrival to the laboratory the pill was checked with the Vitalsense monitor for correct functioning. Throughout the experiment the Vitalsense monitor wirelessly tracked and recorded T_{core} measurements from the 'temperature pill' up to 4 times per minute. On completion of the experiment the data was downloads using the RS-232 download cable and was analysed using the Vitalsense Application software (version 1.12)

2.6 Analysis

Calculations for gross and regional sweat loss are outlined below. Analysis of skin temperature and all statistical analysis are described

2.6.1 Gross Sweat Loss

Gross sweat loss (GSL) was calculated based on the weight change of each participant across each test period and adjusted for fluid intake Calculations are presented in grams and grams per surface area per hour in equations (2 8) and (2 9) respectively.

$$GSL(g) = w_{b1} - w_{b2} + fluid \tag{2 8}$$

$$GSL(g\,m^{-2}\,h^{-1}) = \frac{\left[\frac{(w_{b1} - w_{b2} + fluid)}{SA}\right]}{t} 3600 \tag{2 9}$$

Where;

w_{b1} body weight at start of experiment (kg)

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

fluid total fluid consumption (kg)

t time: duration of intensity or experiment (s)

Corrections were made for respiratory and metabolic mass loss Evaporative loss from respiration (E_{res} , Watts) was calculated using equation (2 10), based upon work described by Livingston *et al.* (1994)

$$E_{res} = 1.27 \cdot 10^{-3} \; M(59\,34 + 0\,53 \cdot T_a - 11.69 \cdot P_a) \qquad (2\,10)$$

And converted into mass loss (g)

$$Mass\ Loss = E_{res} \cdot t \cdot \frac{1}{2430} \qquad (2.11)$$

Where;

E_{res} evaporative loss from respiration (W)

M metabolic rate (W)

T_a air temperature (°C)

t time· duration of intensity or experiment (s)

2430.. latent heat of evaporation of 1 gram of water (J g^{-1})

Metabolic mass loss (g) was calculated from an equation taken from Bakkevig and Nielsen (1995), based upon Kerslake (1972, Pp. 121)·

$$\text{Metabolic mass loss} = \left(\frac{V\,o_2(44 \cdot RQ - 32)}{22\,4} \right) \cdot t \qquad (2.12)$$

Where,

$\dot{V}o_2$ rate of oxygen consumption (L.min^{-1})

RQ respiratory quotient (ND)

t time (s)

The respiratory quotient (RQ) was taken as 0 85 for intensity 1 and 1 00 for intensity 2 (Parsons, 2003. pp 135)

2.6.2 Regional Sweat Rate

Regional SR s were calculated from the weight change of each pad, the surface area (SA) of each pad, and the duration of application to the skin Control samples of the materials used in sweat collection were produced to calculate the dry weight per unit area of each material This was required to calculate the SA of each region measured during testing. Preliminary testing conducted on the stability and absorbency of the absorbent material may be observed in Appendix C For each material (Tech Absorbents product 2164, cotton glove, and cotton sock material) the weight per unit area (g m^{-2}) of a series of control samples was determined using calculation (2 13) from the size and weight of each sample:

$$\text{Area specific weight (g m}^{-2}) = \left(\frac{w_c}{a_c}\right) 10000 \qquad (2\ 13)$$

Where,

w_c weight of control material (g)

a_c area of control material (cm^2)

The values for the control samples and the calculated weight per unit area for the absorbent material, cotton glove, and cotton sock material are displayed in Table 2 2, Table 2 3, and Table 2 4 respectively The stability of the weight of the dry samples was established from observing the weight of the multiple samples The weight of the dry samples was very stable, showing only a 1 3%, 2%, and 2 8% coefficient of variation for the absorbent pad, glove, and sock material respectively.

Table 2.2. Control samples of absorbent material used in the calculation of pad surface areas

Sample	Area (cm2)	Weight (g)	g m^{-2}
1	2500 00	45 48	181 92
2	2500 00	44.89	179 56
3	2500 00	45.85	183.40
4	2500 00	44 99	179 96
5	2500 00	46 31	185 24
mean ± SD	**2500 ± 0**	**45.5 ± 0.6**	**182 ± 2.4**

Table 2.3. Control samples of cotton glove material used in the calculation of surface area

Sample	Area (cm2)	Weight (g)	g m^{-2}
1	36	0.73	202.78
2	36	0 69	191 67
3	36	0.71	197 22
4	36	0 72	200.00
mean ± SD	**36 ± 0**	**0.7 ± 0**	**198 ± 4.7**

Table 2.4. Control samples of cotton sock material used in the calculation of surface area

Sample	Area (cm2)	Weight (g)	g m^{-2}
1	100	2 44	244 00
2	100	2 39	239.00
3	100	2 31	231.00
mean ± SD	**100 ± 0**	**2.4 ± 0.1**	**238 ± 6.6**

The mean value of the calculated weight per unit area of the samples was used in the calculation of each pad or cotton material *SA* The *SA* of each individual pad was calculated in meters square (m^2) using equation (2 14) :

$$SA = \frac{w_d}{\left[\left(\frac{w_c}{a_c}\right) 10000\right]} \qquad (2.14)$$

Where,

SA surface area (m^2)

w_d dry weight of material (g)

Based upon the weight change of the each sample, the *SA*, and the length of time the material was applied to the skin during sweat collection, the regional *SR* was calculated in grams per meter square per hour ($g.m^{-2} h^{-1}$) The calculation for *SR* is shown in equation (2.15):

$$SR = \frac{\left[\frac{(w_w - w_d)}{SA}\right]}{t} 3600 \qquad (2\ 15)$$

Where,

w_w wet weight of individual pad/cotton (g)

w_d dry weight of individual pad/cotton (g)

SA surface area of individual pad/cotton (m^2)

t time. duration of pad/cotton application (s)

The mean, median, and standard deviation were calculated for all SR s and used in analysis. Considerable individual variation in SR is well recognised and so the median was calculated because it is less affected by extreme values compared to the mean

2.6.3 Normalised Ratio Sweat Data

Following the calculation of SR for each individual region, these values were normalised for the area weighed median SR of all measured regions (all pads) for each individual and then a median of all individuals was taken Normalised SR allowed standardisation of data over participants and allowed easy identification of 'high' and 'low' sweat regions This is of particular use when comparing participants with large differences in absolute regional SR s, allowing analysis of regional distribution The calculation for a normalised ratio sweat value for an individual region is outlined in equation (2.16)

$$\text{Individual Normalised SR} = \frac{\text{SR}}{\text{median SA weighted SR of all pads}} \qquad (2.16)$$

Where:

SR regional sweat rate ($g.m^{-2}\ h^{-1}$)

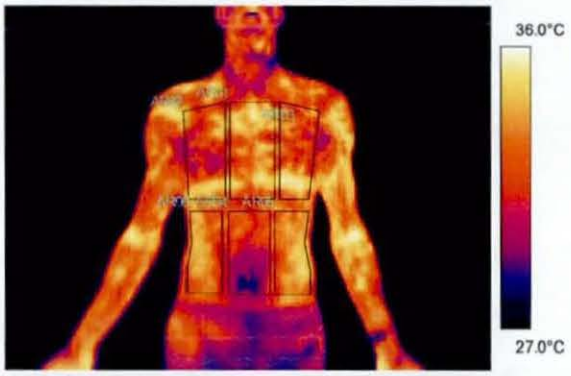
Median surface area weighted sweat rate of all measured pads ($g\ m^{-2}.h^{-1}$)

Using the individual ratio values calculated in equation (2.16), a median normalised ratio sweat value for each region can then be calculated for all participants (2.17)·

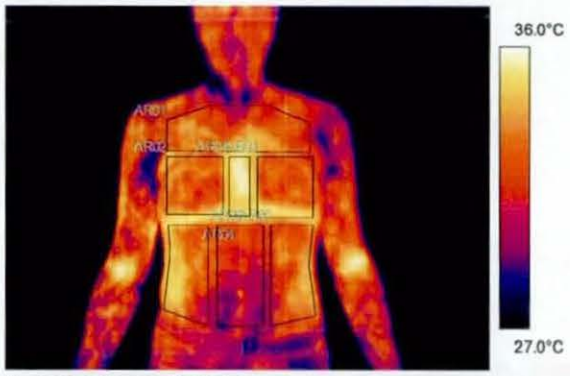
$$\text{Median Normalised SR} = \frac{\text{median normalised ratio of all individuals}}{\text{median SA weighted SR of all pads}} \qquad (2.17)$$

2.6.4 Infra Red Analysis

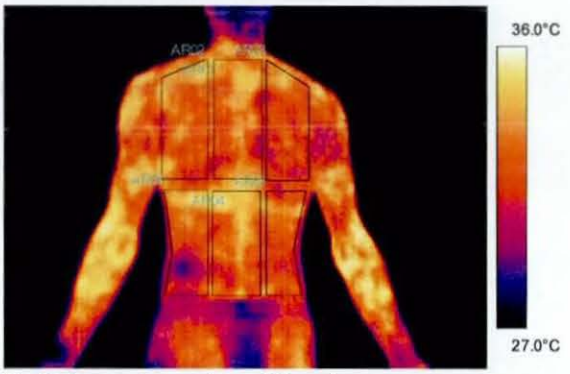
Regional T_{sk} was measured over skin areas corresponding to the location of the absorbent pads. The locations of the regions analysed for both males and females are illustrated in Figure 2.6.



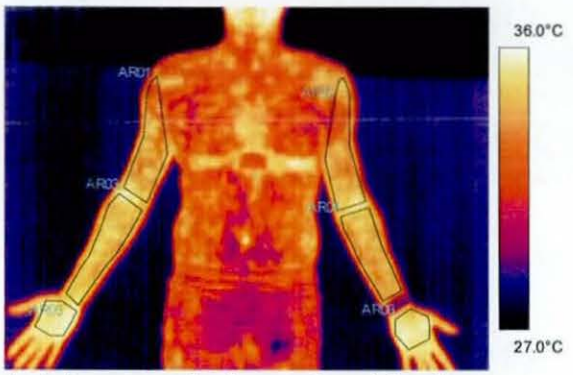
Anterior torso: male



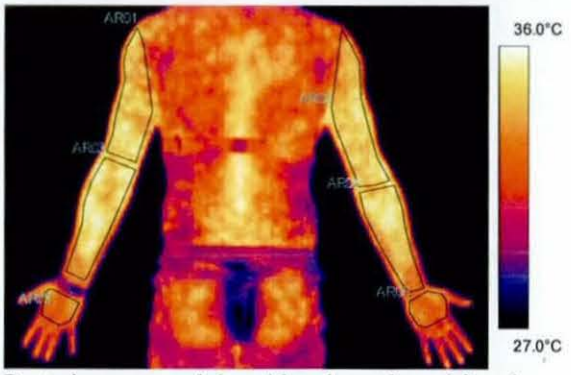
Anterior torso: female



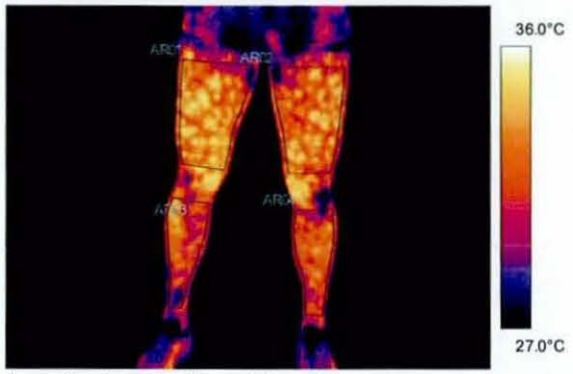
Posterior torso: male and female



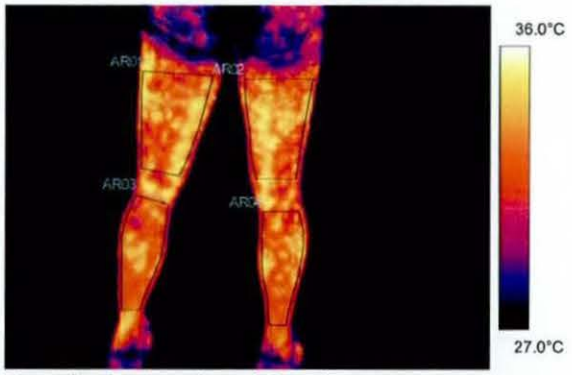
Anterior arms and palms: male and female



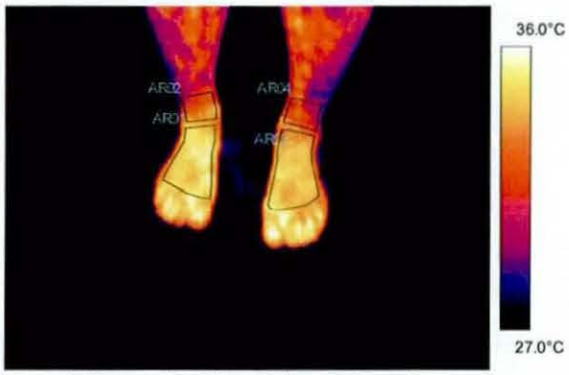
Posterior arms and dorsal hands: male and female



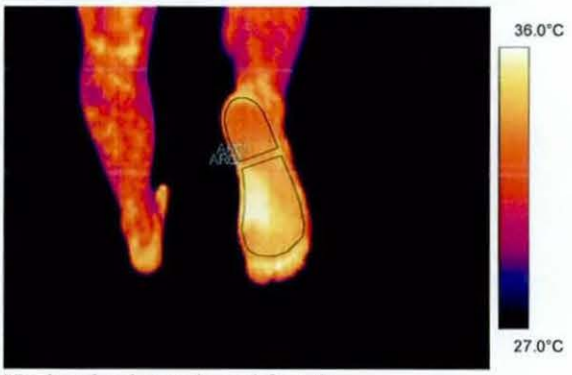
Anterior legs: male and female



Posterior legs: male and female



Dorsal foot and ankle: male and female



Heel and sole: male and female

Figure 2.6. Infra red analysis for measurement or regional skin temperature for all body mapping experiments.

Mean T_{sk} was calculated from regional data for larger body segments where appropriate, for example when comparing the anterior and posterior torso.

2.6.5 Statistical Analysis

Statistical analysis was performed using SPSS (Statistical Package for the Social Sciences, version 16.0, Chicago. USA). Regional *SR* data were initially analysed for differences in corresponding right-left zones. Paired t-tests were performed on all relevant zones and Bonferroni correction was applied to adjust for multiple comparisons. Regional sweat data were grouped accordingly and analysed for differences between individual regions (or groups of regions). Regional data were treated as repeated measures with each region acting as a variable. A one-way repeated measures ANOVA was performed with post hoc multiple comparisons. Considering the large number of regions, multiple comparisons were performed with the risk of inflating type I error. It was decided to apply Bonferroni correction to adjust for multiple comparisons whilst considering the risk of inflating type II error. On balance, both corrected and

uncorrected p values were presented, particularly considering the exploratory nature of the research and the low participant numbers (Perneger 1998, Bender and Lange 1998) The issue of multiple comparisons and the conservative nature of Bonferroni correction were recognised during all analysis.

A comparison of *SR* s within each region from I1 to I2 was performed using a series of paired t-tests and corrected for multiple comparisons (Bonferroni). Male and female regional *SR* data were compared using independent samples t-tests for all corresponding zones. Similarly to all other analysis involving multiple comparisons, Bonferroni correction was applied and data were presented both corrected and uncorrected Regional T_{sk} data were analysed using the same method as for regional *SR* data

Analysis of the relationship between two variables was assessed using a Pearson's r correlation. In particular, Pearson's r correlation coefficients were produced for *GSL* and a number of anthropometric, fitness ($V O_{2\ max}$) and work (metabolic rate) measurements

Chapter 3

Study 1: Effects of Wind Condition on Sweat Rate and Skin Temperature

3 Chapter Summary

A study investigating the effect of the presence of wind and its direction upon regional T_{sk} and SRs of the torso was conducted. Participants completed 30 minutes of steady state exercise on a cycle ergometer in three separate wind conditions (no wind, front wind, back wind). A further five minutes exercising at the same intensity was required during each session to allow sweat collection using absorbent pads. Regardless of the wind direction, the area weighted SR was always higher on the posterior than the anterior torso. The ratio of anterior to posterior SR did not change significantly between wind conditions. No significant difference in T_{sk} was present between the anterior and posterior torso during any wind condition.

3.1 Introduction

Alterations in the heat transfer capacity of the environment have an important impact upon the efficiency of heat dissipation from the body. In moderate and hot conditions, evaporation is the primary avenue for heat loss from the body. In conditions where a positive temperature gradient is present between the body and environment, heat loss occurs via K, C, and R. In the presence of forced air movement, both convective and evaporative heat loss coefficients are greater, increasing heat loss from the body and leading to lower T_{core} and T_{sk} A lower whole body SR may be observed due to a lower T_{core} and T_{sk} compared to conditions with no air movement (Shaffrath and Adams, 1984; Adams *et al*, 1992). As a result of an increase in both h_e and E_{max} with increasing v, a subsequently lower skin wettedness results in an increased sweating efficiency. In the presence of high air velocity, sweat may be removed as moisture from

the surface of the skin before it can evaporate and is therefore be of no thermoregulatory benefit

Since the presence of wind may affect total SR, it may also affect local SRs through its effect of lowering T_{sk}. Havenith *et al* (2008) observed lower regional SRs on the anterior compared to posterior torso in the presence of front wind. The question of whether the front wind caused this difference may therefore be raised To investigate this, regional SRs and T_{sk} of the torso were measured following 30 minutes cycling in a front wind (fw), back wind (bw), and no wind (nw) condition. The environmental conditions were identical to those described in Chapter 2 (2 5.1. Experimental set-up) in order to determine whether the findings from the sweat mapping testing were dependent upon wind direction. Both convection and evaporation in the present experiment would therefore be similar to those in sweat mapping testing, as opposed to controlling for convective heat losses and testing only evaporative effects Experimental work was conducted jointly by the author and Mr J Dovey The author assisted in the supervision of Mr J. Dovey as part of his BSc dissertation work. The author designed the experiment and analysed the raw data independently for inclusion in this thesis

3.2 Methods

Sweat mapping of the torso was conducted to explore the effect of wind direction upon both gross and regional sweat loss and skin temperature All participants completed a pre-test session and three experimental sessions The experimental methodology is outlined in detail in chapter 2, however where differences are apparent, further explanation has been provided in the current chapter

3.2.1 Participants

Eight male participants were recruited from the student population at Loughborough University All participants were physically active however no selection criterion of aerobic fitness was implemented due to the repeated measures design of the study.

3.2.2 Pre-test Session

The pre-test session involved anthropometric measurements of height, weight and dimensions of the upper body necessary for the production of the absorbent pads (Appendix B). All anthropometric measurements were identical to those outlined in Chapter 2 (2.3.1. Anthropometric Measurements; 2.4.1. Absorbent Pads of the Torso) A non-athlete population was used in the current study, requiring a population-specific *SKF* regression equation for healthy (non obese) Caucasian males aged 18-61 years (Chapter 2. 2.3.3, equation 2.3), as defined by Jackson and Pollock (1978, cited in Heyward and Wagner, 2004). Measurements were taken from 3 sites (abdomen, thigh, and chest), used to calculate Db. BF (%) was subsequently calculated using Siri's equation (1956, cited in Heyward and Wagner, 2004 (Chapter 2 2 3 3, equation 2 4)).

3.2.3 Methodology

The experimental methodology for the current study follows that outlined in Chapter 2 (2.5. Generic Sweat Mapping Protocol) with the exception of the use of a cycle ergometer (Lode Excalibur, Lode BV, Groningen, Netherlands) as the means of exercise to allow a more exact control of the participants position relative to the wind source In addition only one exercise intensity was performed for 30 minutes and was directly followed by T_{sk} and regional SR measurements. The calculations and preparation of absorbent pads and plastic sheeting were identical to that outlined in Chapter 2 (2 4.1 Absorbent Pads of the Torso, 2 4 4 Weighting of Absorbent Pads). Three identical experiments were performed on all participants, measuring regional SR s of the torso during exercise in fw, bw, and nw conditions. The order of wind condition was counter balanced to prevent any order effect and experiments were separated by a minimum of 24 hours. Participants were advised on fluid intake for maintenance of euhydration and to avoid alcohol consumption and high intensity exercise within 24 hours of testing They were also requested to abstain from caffeine and food consumption within 2 hours of testing.

3.2.3.1 Experimental Set Up

All experiments were conducted in a climate controlled laboratory at 25°C and 50% relative humidity. Exercise was performed on a cycle ergometer, placed inside a custom made wind tunnel with 2 fans in a vertical configuration to ensure equal coverage over the body. Air velocity was maintained at 2 $m.s^{-1}$ with the direction being determined by the direction of the bike at a fixed distance from the fans. Regular calibration of air velocity was performed using a hot wire anemometer (model TSI Alnor 8455. TSI Instruments Ltd, High Wycombe, UK. Range 0.125-50 $m.s^{-1}$.) at the position of the cycle ergometer seat. Data output was recorded on a Eltek/Grant 10 bit, 1000 series squirrel data logger (Grant Instruments, Cambridge, England) at 30 second intervals.

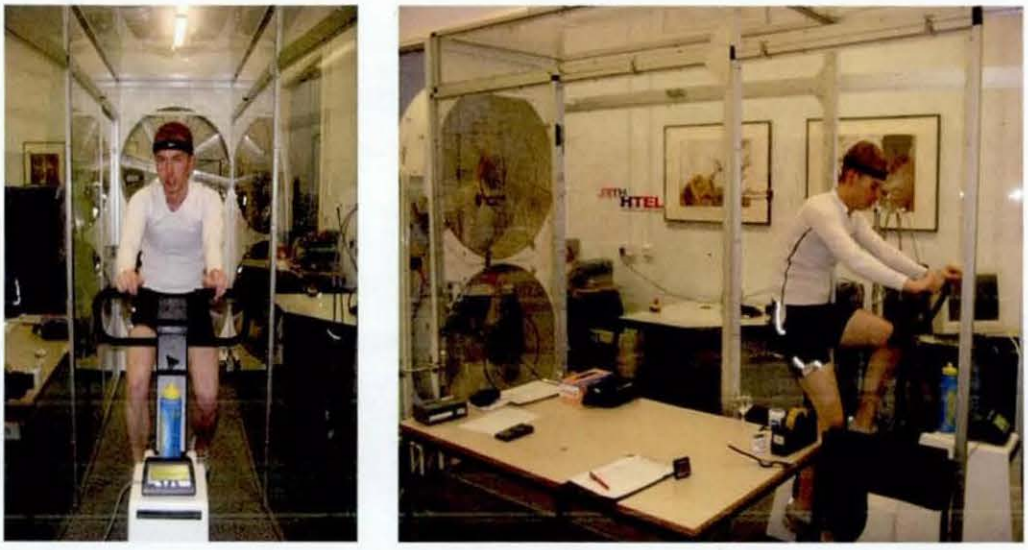


Figure 3.1. Experimental set up of the cycle ergometer and wind tunnel.

3.2.3.2 Experimental Protocol

Body weight and sublingual temperature were recorded upon arrival at the laboratory and immediately after each experiment. Participants were provided with a t-shirt (Quechua, Decathlon, France) and lycra shorts (Quechua Novadry; Decathlon, France) for testing, but were required to wear their own socks and trainers. *BL* infra red images (Thermacam B2, FLIR Systems Ltd., West Malling, Kent, UK) of the torso were taken of nude, dry skin for analysis of regional T_{sk}. Participants attached a heart rate monitor and watch (Polar Electro Oy, Kempele, Finland) before remaining seated in the laboratory for five minutes to establish resting heart rate. Following any desired adjustments to the cycle ergometer, the required wind condition was initiated and

exercise commenced for a duration of 30 minutes, with heart rate recorded every five seconds. The initial five minutes of cycling was used to warm up and achieve an appropriate workload based on heart rate The intensity was self determined but was requested to be maintained for the full exercise period and across all experiments. Immediately following the 30 minute exercise period, participants removed their t-shirt and heart rate monitor before towelling down for infra red images of the torso. Absorbent pads, attached to custom sized plastic sheeting, were applied to the torso and secured in place using a long sleeved stretchy zip t-shirt. The pad application process was timed with a stop watch and immediately followed by a further five minute period on the bike, at the same exercise intensity as previously performed. The absorbent pads were removed at the end of the five minutes and immediately sealed in individual airtight, zip-lock bags. Infra red images of the torso were taken of towelled dry, nude skin before the participant was weighted and a measurement of sublingual temperature was taken. All drinks bottles were weighed to allow calculation of fluid intake and subsequent adjustments to *GSL* (Chapter 2. 2.6 1. Gross Sweat Loss) All pads were weighed inside their individually labelled airtight bags and calculations of regional absolute and normalised *SR* ($g\ m^{-2}\ h^{-1}$) were made (Chapter 2: 2.6.2. Regional Sweat Rate, 2.6 3 Normalised Ratio Sweat Data).

3.2.4 Analysis

Statistical analysis were conducted using the Statistical Package for the Social Sciences version 16 0 (SPSS Inc , Chicago, IL, USA version 16 0) Analysis of the main effects of wind direction and region were treated as a repeated measures design, using a two way repeated measures ANOVA for both variables Post hoc pairwise comparisons were performed to analyse individual differences, both with and without Bonferroni correction.

3.3 Results

3.3.1 Participants

The physical characteristics of the participants involved in the wind direction study are provided in Table 3.1. The variability in characteristics were expected since no

Table 3.1. Participant characteristics for wind direction experiments Weight, gross sweat loss (GSL), heart rate, and predicted VO_2 are calculated as the overall mean from all wind conditions, displayed in italic

Participant no	Age (yrs)	Height (cm)	Weight (kg)	Surface area (m^2)	Body Fat (%)	Av. total GSL based on mass loss (g)	Av. total GSL based on mass loss ($g\ m^{-2}.h^{-1}$)	HR at 25 min (bpm)	Av $V0_2$ during exercise ($ml\ kg^{-1}.min^{-1}$)
w1	20	183 5	77 38	2 00	13 9	394	295	134	17 6
w2	21	194 2	92 59	2 25	12 2	596	397	130	25 3
w3	20	204 0	85 91	2 26	9 6	205	136	134	16 5
w4	20	172 5	70 84	1 85	11 8	364	295	141	20 7
w5	21	184 0	92 90	2 16	14 8	439	305	133	23 6
w6	20	189 5	72 11	1 98	7 5	562	426	136	27 2
w7	21	187 0	81 23	2 07	10 0	482	349	131	21 1
w8	21	180 3	70 05	1 90	10 5	511	404	132	28 1
mean ± SD	**21 ± 1**	**186 9 ± 9 4**	***80.4 ± 8 9***	**2.06 ± 0 2**	**11.3 ± 2.4**	***444 ± 155***	***326 ± 93***	***134 ± 5***	***22.5 ± 4.2***

inclusion criteria were set for body composition or fitness level due to variation across wind conditions being assessed within each participant

3.3.2 Core Temperature

Sublingual temperature increased significantly during only the *fw* condition ($p < 0.05$), from a *BL* value of 36.5 ± 0.4°C to 37.0 ± 0.3°C. In addition to sublingual temperature measurements on all participants, a CorTemp™ ingestible temperature pill (Mini Mitter Company, Inc. Bend, Oregon, USA) was swallowed by participant w8 five hours prior to each session. Mean T_{core} was calculated over the final five minutes of exercise and compared between wind conditions (Table 3.2).

Table 3.2. Mean core temperature (T_{core}), heart rate and gross sweat loss (GSL) over the whole experiment for participant w8 during each wind condition: no wind (nw), front wind (fw), back wind (bw).

Condition	T_{core} (°C)	HR (bpm)	GSL ($g.m^{-2}.h^{-1}$)
nw	37.7	128	398
fw	37.8	132	405
bw	38.0	136	407
mean ± SD	**37.8 ± 0.2**	**132 ± 3.3**	**211 ± 17**

Participant w8 showed little difference between experiments in T_{core}, with an increase of 0.47°C, 0.67°C, and 0.66°C over the duration of the experiment for *nw*, *fw*, and *bw* respectively. Heart rate and *GSL* were similar for all experiments, illustrated by the small standard deviation.

3.3.3 Gross Sweat Loss

GSL was calculated for all experiments from the total weight change of each participant and adjusted for fluid consumption and respiratory and metabolic losses (Chapter 2. 2.6.1 Gross Sweat Loss. Equations 2.8 to 2.12). *GSL* from all wind conditions are

presented in grams and grams per surface area (g $m^{-2}.h^{-1}$) for each participant in Table 3 3.

Table 3.3. Gross sweat loss in grams and grams per surface area for the no wind (nw), front wind (fw), and back wind (bw) conditions with standard deviation (SD) of all wind conditions for individual participants

	Gross Sweat Rate							
	g				$g\ m^{-2}.h^{-1}$			
Participant	NW	FW	BW	SD	NW	FW	BW	SD
w1	500	348	334	**92**	375	261	250	**69**
w2	794	461	532	**176**	530	307	355	**117**
w3	216	155	244	**45**	143	103	162	**30**
w4	283	527	283	**141**	229	427	229	**114**
w5	470	462	385	**47**	327	321	268	**33**
w6	816	467	402	**222**	618	354	304	**169**
w7	503	438	505	**38**	365	317	366	**28**
w8	504	513	516	**6**	398	405	407	**5**
mean	**511**	**421**	**400**		**373**	**312**	**293**	
median	**502**	**462**	**394**		**370**	**319**	**286**	
SD	**212**	**121**	**110**		**152**	**100**	**81**	

No significant differences in *GSL* were present between any wind condition Large variation was observed between participants with a range of 475 g $m^{-2}.h^{-1}$ in the *nw* condition, although this was not unexpected since they exercised at different absolute workloads. The within subject variation was also large between experiments, as evidenced by the standard deviation of all experiments presented for all individual participants in Table 3.3. In particular, a standard deviation of 169 g $m^{-2}\ h^{-1}$ was observed for participant w6, showing a difference of 314 g $m^{-2}\ h^{-1}$ between wind conditions

3.3.4 Regional Sweat Rate

The primary aim of the regional *SR* data analysis was to assess the effect of wind direction upon anterior and posterior *SR* rather than distribution within these regions Regional *SR* data was therefore area weighted for the 1) anterior torso, 2) posterior torso, and 3) shoulders and sides, in all individuals and then an average taken The area weighted data was normalised for the area weighted median *SR* of all the regions covered by pads. The ratio values created enables analysis of sweat distribution devoid of the effect of individual differences in absolute *SR* s A value of one indicates a *SR* equal to the area weighted median *SR* of all regions measured Values above or below

one indicate *SR* s higher or lower than the area weighted median *SR* of all regions measured respectively Absolute *SR* and normalised ratio values for each region, in addition to the *SA* weighted *SR* for each wind condition are presented in (Table 3.4).

Table 3.4. Median absolute area weighted regional sweat rates and normalised ratio data for the no wind (nw), front wind (fw), and back wind (bw) conditions Overall surface area (SA) weighted mean sweat rate for all of the torso pads during each wind condition

	Absolute sweat rate ($g\ m^{-2}.h^{-1}$)			Normalised ratio data		
Region	**NW**	**FW**	**BW**	**NW**	**FW**	**BW**
anterior	260**#	104**#	158*#	0 87**##	0 80**##	0 88**#
posterior	338	192	215	1 27	1 32	1 26
sides & shoulders	266**##	101**#	127*#	0 80**##	0 81**##	0 79**##
SA weighted mean SR of sampled regions ($g\ m^{-2}\ h^{-1}$)	286	170	193			

Regional comparison within wind conditions
significant difference from the posterior torso is denoted by * at p < 0 05, and ** at p < 0 01
significant difference from the posterior torso is denoted by # at p < 0 05, and ## at p < 0 02
following Bonferroni correction

During all wind conditions, the posterior torso showed significantly higher absolute and normalised ratio *SR* s than the anterior torso and the sides and shoulders, both with and without Bonferroni correction. No significant differences in *SR* were present between the anterior torso and sides and shoulders during any wind condition Absolute *SR* for each region was compared across all wind conditions, with all three regions being significantly higher during the *nw* condition compared to *fw* and *bw* (anterior: *nw* vs *bw* P < 0 01, *nw* V *fw* p < 0 001, posterior p < 0.001; sides p < 0 01) Regional *SR* on the anterior torso was significantly higher in the *bw* compared to *fw* condition (p < 0 01), but not for the other two regions.

The normalised ratio data illustrates that the posterior region exhibits the highest *SR* over the torso during all wind conditions As expected, the posterior torso showed a higher ratio value in the *fw* than the *bw* condition, since it may be expected that an increase in both convective and evaporative cooling on the anterior torso would result in a lower *SR* in that region. Surprisingly, there was however no significant difference in regional T_{sk} at any measurement period, indicating no difference in cooling No significant change in regional *SR* distribution was apparent when a ratio of the anterior

to posterior normalised SR was calculated, producing values of 0.69, 0 61, and 0 70 for the nw, fw, and bw conditions respectively

3.3.5 Skin Temperature

Regional T_{sk} was analysed for differences both within and between measurement periods for all three wind conditions (Table 3.5) Post hoc pairwise comparisons within wind conditions showed no significant difference in T_{sk} between the anterior and posterior torso at any measurement period. The majority of the differences were between the anterior torso and the sides Following Bonferroni correction no significant differences were present between regions, however one comparison showed a p value less than 0 1 (anterior vs left side, p = 0.058) Mean skin temperature ($\overline{T}_{sk}$; not area weighted) for nw, fw, and bw were compared at each measurement period (Table 3.5) The nw condition exhibited a significantly higher $\overline{T}_{sk}$ than the other two conditions at pre and post pad application No significant differences in T_{sk} were present at baseline (BL), and no significant differences were present between fw and bw at any measurement period

Regional T_{sk} for each wind condition over each measurement period are presented in Figure 3 2 Regional T_{sk} showed no significant differences between fw and bw for any corresponding region at any measurement period, with exception to the posterior torso being significantly higher in the bw condition compared to fw at BL ($p < 0.05$). T_{sk} was significantly higher at all regions during nw compared to both fw and bw at pre and post pad application, with exception to the left side at post pad application, where

Table 3.5. Regional skin temperature at baseline (BL), pre, and post pad application during no wind (nw), front wind (fw), and back wind (bw).

	Regional Skin Temperature (°C)								
	Baseline			Pre pads			Post pads		
Region	**NW**	**FW**	**BW**	**NW**	**FW**	**BW**	**NW**	**FW**	**BW**
anterior	33 0 ± 1 5	32 6 ± 1 5	33 6 ± 1 0	33 3 ± 1 0	31 5 ± 1 3$	32 2 ± 0 6	33 8 ± 1 1	32 7 ± 1 3	32 9 ± 0 7
posterior	32 6 ± 1 4	32 6 ± 1 3	33 6 ± 1 0	33 4 ± 1 1	31 7 ± 1 2	31 9 ± 0 9	34 2 ± 0 8	33 0 ± 1 5	32 9 ± 0 8
right side	32 5 ± 1 0	32 4 ± 1 6	33 1 ± 0 8*	33 3 ± 1 0	32 0 ± 1 6*	32 2 ± 1 1	33 8 ± 0 6	32 7 ± 1 5	32 6 ± 1 0
left side	32 5 ± 1 2*	32 3 ± 1 5	33 4 ± 0 7*^	33 5 ± 1 0	32 2 ± 1 4**	32 4 ± 0 8	34 1 ± 0 6	33 1 ± 1 4*	33 1 ± 0 7
Overall mean ± SD	**32.6 ± 1.2**	**32.5 ± 1.4**	**33.4 ± 0.8**	**33 4 ± 0.9**	**31.8 ± 1.3£ #**	**32.2 ± 0.8££ #**	**34.0 ± 0.7**	**32.9 ± 1.4£ §**	**32.9 ± 0.7££ ##**

* denotes a significant difference from the anterior torso at $p < 0\ 05$
** denotes a significant difference from the anterior torso at $p < 0\ 01$
^ denotes a significant difference from the right side at $p < 0\ 05$
$ denotes a significant difference from the left side following Bonferroni correction at $0\ 1 > p \geq 0\ 05$

£ denotes a significant difference from NW at $p < 0\ 05$
££ denotes a significant difference from the NW condition at $p < 0\ 01$
# denotes a significant difference from NW following Bonferroni correction at $p < 0\ 05$
denotes a significant difference from NW following Bonferroni correction at $p < 0\ 01$
§ denotes a significant difference from NW following Bonferroni correction at $0\ 1 > p \geq 0\ 05$

no significant difference was present between *nw* and *fw*. At *BL*, significance was present at the posterior torso only, with the *bw* condition being greater than both *nw* and *fw* (*nw* $p < 0.05$; *fw* $p < 0.05$). The majority of these differences remained significant following Bonferroni correction.

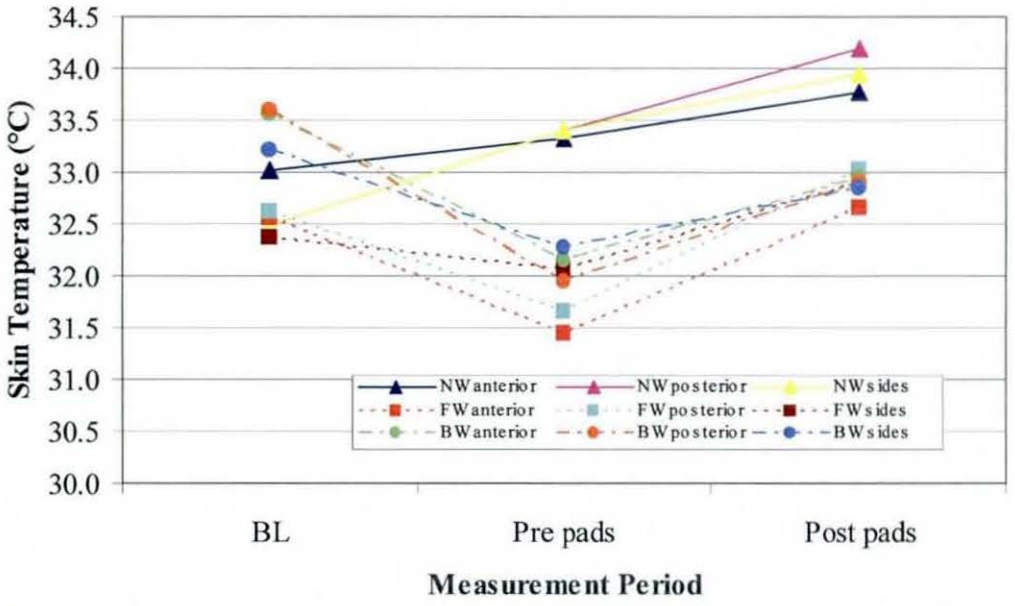


Figure 3.2. Regional skin temperature of the torso at baseline (BL), pre and post pad application during three wind condition; no wind (*nw*), front wind (*fw*), and back wind (*bw*).

The significantly higher regional T_{sk} during the *nw* condition compared to *fw* and *bw* is clearly evident in Figure 3.2. A significant main effect of measurement period was present only in the *bw* condition ($p < 0.01$), with a significant difference between the *BL* and pre pad periods both with ($p < 0.05$) and without ($p < 0.01$) Bonferroni correction. Significant differences were present between the pre and post pad application periods in all conditions (*nw* $p < 0.01$; *fw* $p < 0.05$; *bw* 0.01), remaining significant following Bonferroni correction (*nw* $p < 0.05$; *fw* 0.05), with exception only to the *bw* condition which had a p value less than 0.1 ($p = 0.087$). Notably, the absolute change in T_{sk} (ΔT_{sk}) from pre to post application was greatest in the FW and *bw* conditions, reflecting the decrease in T_{sk} from BL compared to the increase observed in *nw*, where evaporative cooling was less. The greatest absolute ΔT_{sk} from pre to post pad application occurred on the posterior torso in all wind conditions, with

values of 0.8 ± 0.4°C, 1.4 ± 1 0°C, and 1 0 ± 0 8°C during *nw*, *fw*, and *bw* respectively.

3.4 Discussion

3.4.1 Core Temperature

One participant ingested a core temperature pill for each experiment since no differences in T_{core} were anticipated between conditions due to using an identical workload T_{core} was similar for participant w8 during all experiments, with values of 37 7°C, 37.8°C, and 38 0°C for the *nw*, *fw*, and *bw* conditions respectively. The mean (±SD) calculated work rate of all participants (VO_2) was similar in all conditions (*nw* 22.2 ± 5 ml $kg^{-1}.min^{-1}$, *fw*, 22.6 ± 4 ml kg^{-1} min^{-1}; *bw* 22 8 ± 4 $ml.kg^{-1}$ min^{-1}), so one might expect T_{core} to be higher in the *nw* condition as a result of a lower convective and evaporative heat loss than in the other two conditions. Under conditions of high air velocity, the efficiency of heat loss from the body is increased, often resulting in a lower T_{core}, T_{sk}, and *SR* (Nadel *et al.* 1971b, Nadel, 1979, Adams *et al.*, 1992) There was however no significant different in *GSL* between experiments suggesting little affect of the presence or direction of 2 $m.s^{-1}$ air velocity upon the cooling dynamics of the body Candas *et al* (1979b) observed notable differences in evaporative efficiency of sweating at air velocities as low as 0 2 m s^{-1}, stating that values of less than 0.4 m s^{-1} are in the range of free convection This suggests that the air velocity in the current study is sufficient to alter cooling dynamics The short duration of exercise and moderate intensity may however contribute to the non significant difference in T_{core}. Studies concerning air velocity, *SR*, and T_{core} typically involve exercise for a greater duration and/or higher workloads than in the current study (Adams *et al*, 1992, Saunders *et al*, 2005)

3.4.2 Gross Sweat Loss

GSL varied greatly between participants since they were required to exercise at a workload which they were able to maintain for the duration of the exercise period Each participant exercised at the same workload for all three of their experiments to allow an

accurate comparison of conditions. The *nw* condition showed the highest *GSL* with a mean of 205 ± 85 g m^{-2} h^{-1}, followed by the *fw* then *bw* conditions with values of 170 ± 54 g $m^{-2}.h^{-1}$ and 159 ± 45 g.$m^{-2}.h^{-1}$ respectively. Though, due to the high intra individual variability, these differences were not significant, despite the differing wind conditions potentially altering both convective and evaporative heat transfer coefficients, and affecting the efficiency of heat dissipation from the body (Nadel, 1979; Adams *et al.*, 1992). Shaffrath and Adams (1984) observed a lower whole body *SR* resulting from a lower T_{core} and T_{sk} in conditions of 4-5 m s^{-1} air velocity compared to conditions with no forced air movement. Conversely, Nadel *et al* (1971b) observed a reduction in local *SR* in participants exercising in moderately warm condition with increased air velocity, yet a greater whole body evaporative rate. In the current study, an air velocity of 2 m s^{-1} was used to mimic the air velocity used in future sweat mapping experimentation. This air velocity did not appear to alter *GSL* in clothed males cycling for 30 minutes in the present environmental conditions.

3.4.3 Regional Sweat Loss

Similarly to *GSL*, large variation existed between participants in regional sweat loss due to differences in absolute workload and cardiovascular fitness As expected, absolute regional *SR* s over the torso were significantly higher in the *nw* condition compared to the two wind conditions, resulting from a lesser environmental capacity for heat dissipation. Within each wind condition, the posterior torso demonstrated a significantly higher *SR* than the other regions Unexpectedly, the posterior torso showed a higher absolute *SR* during the *bw* compared to the *fw* condition, although this difference was not significant Since the evaporative and convective heat transfer coefficients would be higher for the posterior torso during the *bw* condition, the reverse would have been expected As observed by Nadel *et al.* (1971b), a decrease in regional *SR* is typically observed with increased air velocity. However, Candas *et al* (1979b) suggest that an increase in local *SR* will result from (an increase) air velocity due to an increase in the heterogeneity of regional rates of evaporation and the same local skin wettedness requirement

From the current data, it is evident that the posterior exhibits the highest SRs over the torso, regardless of the direction of an air velocity of 2.m s^{-1} The presence of air movement significantly reduced absolute SR in all regions. When considering the normalised data, the regional *SR* distribution was altered slightly with wind condition, as evidenced by a small change in the anterior to posterior ratio.

3.4.4 Skin temperature

As expected, a decrease in $\overline{T}_{sk}$ of the torso was observed during the 30 minute exercise period in both the *fw* and *bw* conditions. Although not statistically significant, a decrease of 0 7°C and 1.2°C for the two conditions respectively may be considered biologically relevant. This finding is easily explained by the well documented role of air velocity in increasing evaporative heat loss and decreasing T_{sk} (Kerslake, 1972, Shaffrath and Adams, 1984; Adams *et al*, 1992) Conversely, in a situation of still air, where evaporative heat losses will be lower, T_{sk} will be higher than under conditions of forced convection. This is evident in the present study whereby mean torso T_{sk} increased during exercise by 0 8°C, causing a significant main effect of wind condition ($p < 0\ 01$) at the pre pad application period The significant increase in $\overline{T}_{sk}$ observed between the pre and post pad application in all wind conditions (uncorrected *nw* $p < 0\ 01$; *fw* $p < 0\ 05$; *bw* 0.01) may be explained by the reduction in evaporative heat loss resulting from covering the skin with the absorbent pads The absolute change in regional T_{sk} between pre and post pad application was similar between wind conditions and is therefore not thought to affect T_{sk} comparison. The posterior torso consistently showed the greatest increase during all conditions, with an absolute increase of 0 8 ± 0.4°C, 1 4 ± 1 0°C, and 1 0 ± 0 8°C during *nw*, *fw*, and *bw* respectively

3.5 Conclusions

Following a study to identify the affect of wind condition upon regional and *GSL* in Caucasian male participants, the following conclusions may be drawn·

- No significant difference in *GSL* was present between *nw*, *fw*, *bw* conditions, indicating that the presence or direction of a 2 $m.s^{-1}$ air velocity did not significantly affect *GSL* during 30 minutes cycling in a moderate environment This was however surprising since *GSL* was expected to be significantly higher in the *nw* condition due to lower convective heat loss and h_e requiring a higher *SR* to maintain the same T_{core}.
- Absolute regional sweat rates were significantly higher in the absence of wind
- The posterior torso consistently showed the highest absolute and normalised sweat rate within each wind condition.
- No significant change in distribution of regional sweat rates occurred between wind conditions, with the ratio of the anterior to posterior torso being greatest during the *bw* condition and lowest during the *fw* condition
- Regional differences in sweat rate could not be explained by regional skin temperature. No significant differences in skin temperature were present between the anterior and posterior torso during any wind condition.

Chapter 4

Study 2: Body Sweat Mapping in Male Athletes

4 Chapter Summary

This chapter explores the regional variation in *SR* in male athletes Participants were required to exercise at two different intensities during each experiment, with the whole body progressively mapped over three experiments Considerable variation in gross and regional *SR* was observed both within and between male athletes. Irrespective of the variation in absolute *SR* between individuals, consistent patterns of regional distribution were observed. A significant increase in regional *SR* s occurred with an increase in exercise intensity, with exception of the feet. The central and lower back consistently showed the highest *SR* over the body at both intensities in comparison to the lowest *SR* s being observed on the extremities. The forehead *SR* was significantly higher than all other regions on the head and face, followed by regions on the head, and the lowest *SR* s on the cheeks

4.1 Introduction

A large body of research is available regarding *GSL* in relation to differing thermal states, however little research covers detailed regional variation in *SR* over the body. The limited quantitative data available on regional variation only concentrates on small areas of skin within each region, neglecting the possibility of intra regional variation Regional variation between large body segments has long been recognised (Weiner, 1945; Kuno, 1956; Hertzman, 1957, Cotter *et al*, 1995). Recent research on the foot (Taylor *et al*, 2006, Fogarty *et al*, 2007), torso (Havenith *et al.*, 2008; Machado-Moreira *et al*, 2008a), and head (Machado-Moreira *et al.*, 2008b) have however demonstrated intra regional variation The ventilated capsule method adopted in the majority of these studies, although having the distinct advantage of measuring *SR* continuously over time, only covers small areas of skin. The absorbent method of sweat collection used in this chapter will aim to cover large areas of the skin simultaneously to

allow detailed analysis of inter and intra regional variation in *SR* in male athletes Two series of experiments are described in this chapter One for the sweat mapping of the head, face and neck, the other for the sweat mapping of the rest of the body

4.2 Methods

4.2.1 Participants

Fourteen male participants (m1-m15) were recruited from the student and staff population at Loughborough University. Ten athletes (m1-m10) participated in three body mapping experiments. Nine participants were involved in sweat mapping of the head, face and neck (m4, m6, m7,m9, m11-m15). Inclusion criteria for participants were as follows:

- Caucasian males
- age 18-35 years old
- regular medium/long distance runner (i e minimum 3 times per week/top club level to elite)
- 10k running time less than 40 minutes
- No current injuries/medical conditions preventing subjects running for 60 minutes
- No problem swallowing a radio pill

4.2.2 Methodology

4.2.2.1 Body Mapping

The experimental methodology for body sweat mapping is outlined in detail in Chapter 2 In summary, participants completed a pre-test session in an ambient temperature of 18°C and three identical body mapping experiments at 25°C and 50% *rh*. *SR*s were measured over one third of the body during each session (1: torso, 2: legs, 3. arms, hands, buttocks, and feet) T_{core} was recoded pre and post test (sublingual) and monitored continuously using radio pills during one of the three experiments and recorded at one minute intervals Experimental order was counter-balanced across participants to prevent any potential order effect.

4.2.2.2 Head, Face, and Neck Mapping

In addition to the regions described in Chapter 2, measurements were performed on the head, face and neck in male athletes Sweat mapping of the head, face, and neck was identical in format to the body sweat mapping protocol (Chapter 2 section 2 5 Generic Sweat Mapping Protocol) but with differing pad locations, measurements and application All pad preparation and calculations followed the same principle as shown in Chapter 2.

Participants involved in sweat mapping of the head were required to shave their head prior to testing. Anatomical measurements of the head, face and neck were taken using a tape measure and anthropometer (Harpenden anthropometer, Holtain Ltd , Crymych, Pembs UK) A total of nine head pads (six lateral and three medial), four face pads (cheeks, forehead, and chin) and two arm pads (right anterior and posterior upper arm) were used. The latter acted as a 'control' to compare to the whole body sweat mapping data The locations and corresponding labels for all pads are presented in Figure 4.1 Pad dimensions were calculated and templates were produced using the same principles as for the body sweat mapping (See Appendix B for all measurements and calculations). The templates were traced onto the absorbent material and cut to produce the absorbent pads. Small incisions were made on either side of the head pads and a small triangular piece of material removed. The incisions were taped back together to form three dimensional, slightly concave shapes to fit over the head. They were secured together using medical tape in a lattice formation before being applied to the head. Bandafix® wide elastic mesh bandage (Palmedic, Lichtenvoorde, The Netherlands) was pulled over the head, face, and neck to secure the pads in place during each sweat sampling period (Figure 4.2).

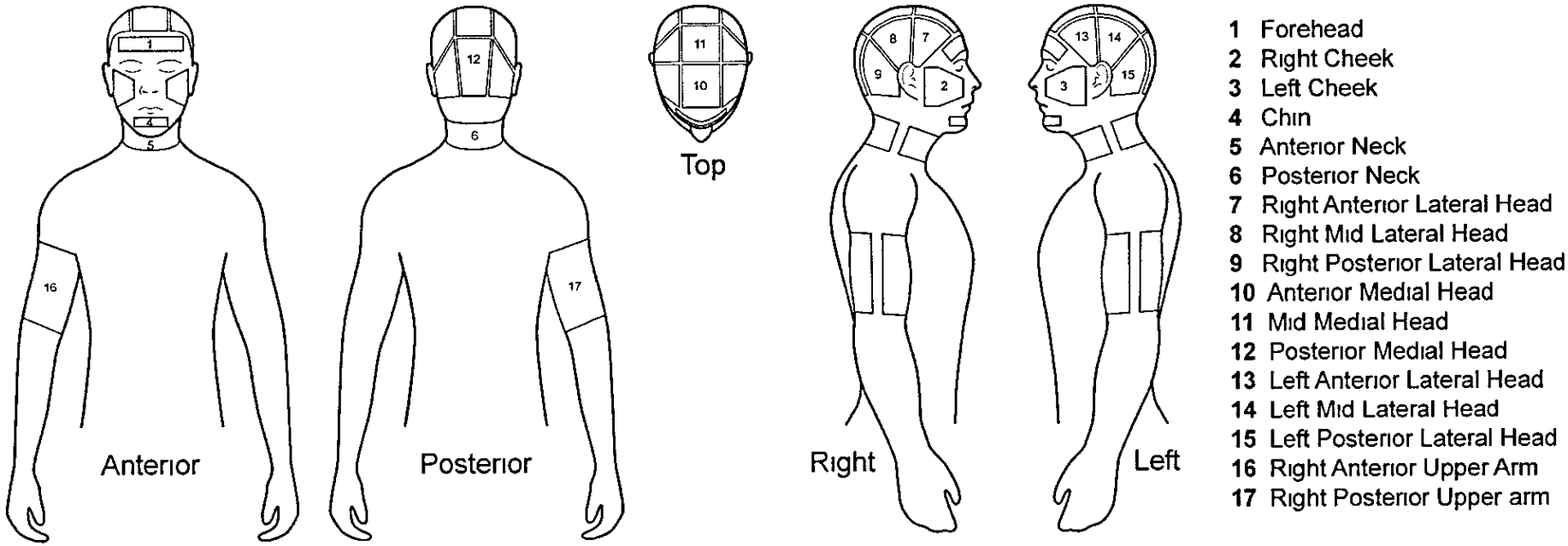
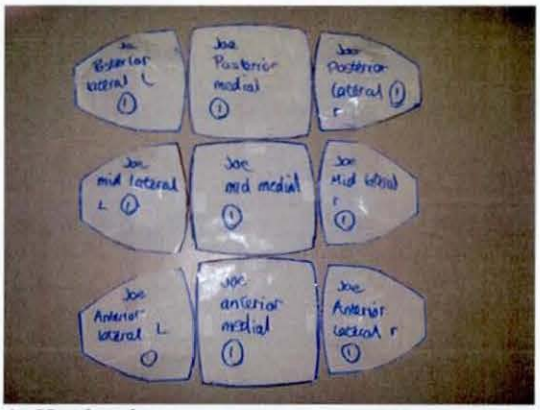
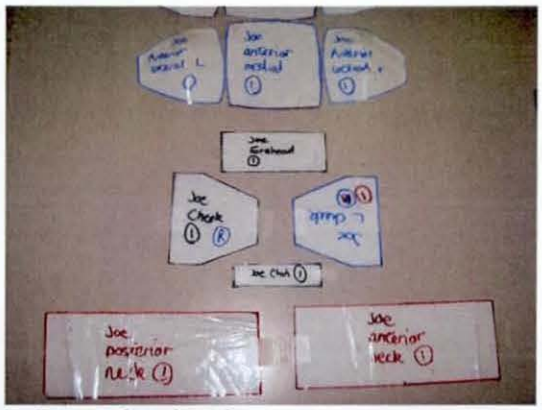


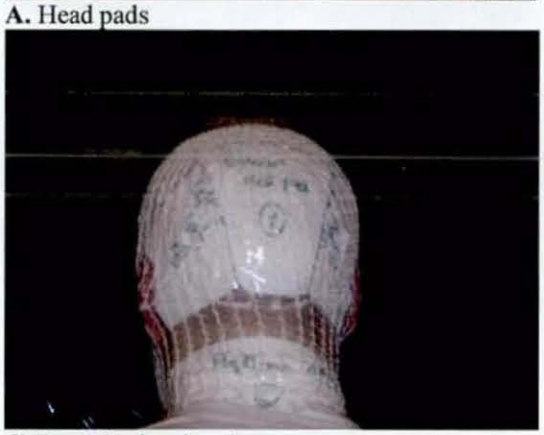
Figure 4.1. Location of absorbent pads for the head, face and neck



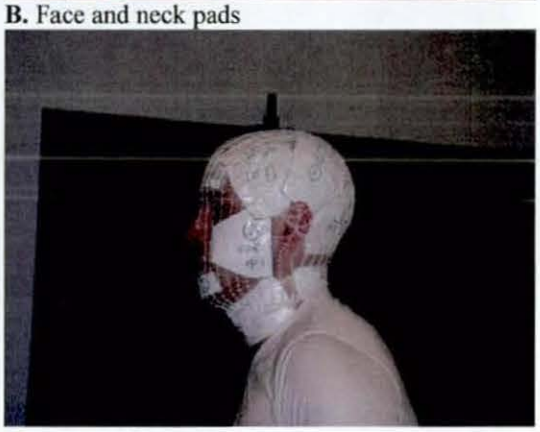
A. Head pads



B. Face and neck pads



C. Posterior head pads



D. Face and lateral head pads

E. Face and neck pads

F. Head, face and neck participant during testing

Figure 4.2. Absorbent pads of the head (A), face and neck (B). Application of absorbent pads to the head (C, D), face and neck (E) with Bandafix® at two exercise intensities (F).

Regional T_{sk} was measured over skin areas corresponding to the location of the absorbent pads. The locations of the regions analysed are illustrated in Figure 4.3.

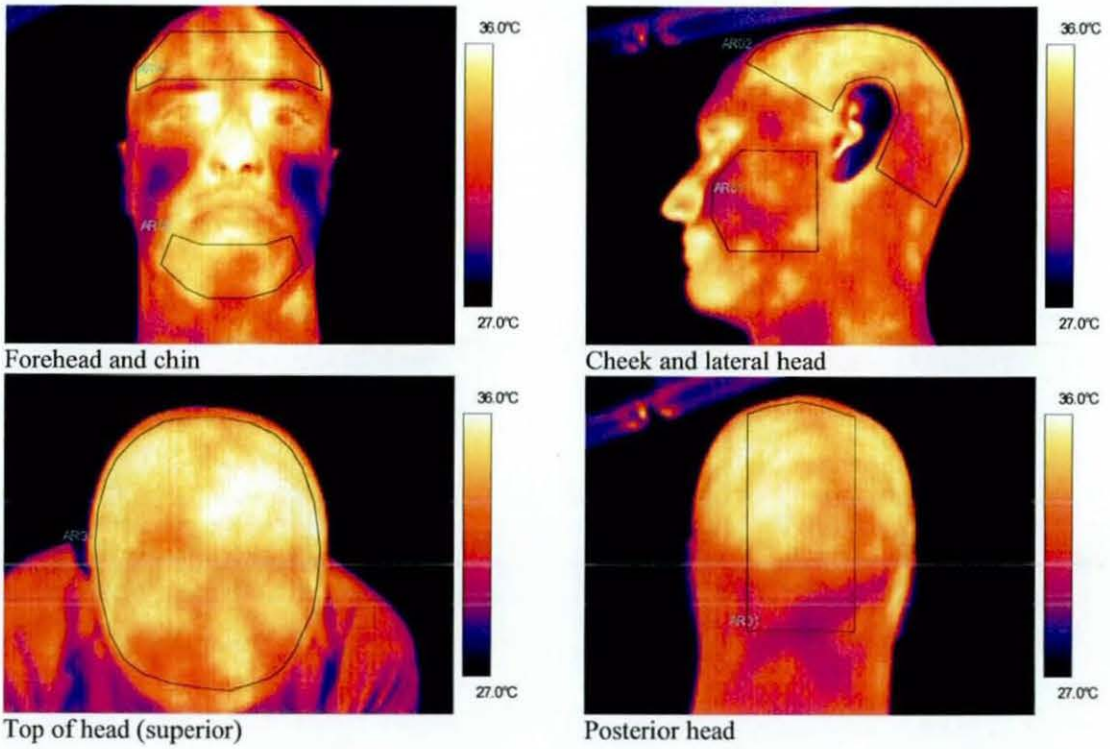


Figure 4.3. Infra red analysis for measurement or regional skin temperature for head, face and neck experiments.

Data analysis for measurements was identical to that used for the sweat mapping experiments (Chapter 2: 2.6 Data Analysis).

4.3 Results

4.3.1 Participants

The physical characteristics of participants involved in the body mapping (m1-m4, m6-m10) and head, face and neck experiments are provided in Table 4.1 and Table 4.2 respectively. Nine of the ten original male participants involved in the body mapping completed the pre-test session and all experimental sessions. Participant 5 withdrew from the study following the pre-test session and one experimental session and has therefore been removed from analysis. All participants listed in Table 4.2 were mapped for *SR* s on the face and neck, but only four participants (m6, m12, m14, m15) provided consent for mapping of the head. No significant differences were present between the body mapping and head groups for any physical characteristics, with exception to $\dot{V}O_{2\ max}$. Head, face and neck participants had a significantly lower predicted $\dot{V}O_{2\ max}$

were observed respectively. Clearly the overlap of participants indicates that those recruited solely for head and face sweat mapping had lower predicted $VO_{2\ max}$ values. Difficulties in recruitment for sweat mapping of the head resulted in lowering the fitness level stated on the preliminary body mapping inclusion criteria. *SR* data for the head and face will subsequently be analysed separately from the main body mapping data. This issue will be addressed when considering both gross and regional *SR*

4.3.2 Environmental Conditions

The mean (±SD) environmental conditions in the temperature controlled room for the body mapping experiments were 25 6 ± 0 4°C and 43 4 ± 7.6 % *rh*. The environmental conditions for the head, face and neck experiments were 25 8 ± 0.4°C and 48 8 ± 3 0 % *rh*.

Table 4.1. Participant characteristics for body sweat mapping Weight, gross sweat loss, and running speed are calculated as the overall mean from all experiments completed, displayed in italic

Participant no	Age (yrs)	Height (cm)	Weight (kg)	Surface area (m^2)	Body Fat (%)	Predicted $V0_{2\,max}$ ($ml.kg^{-1}\,min^{-1}$)	Av. Total gross sweat loss based on mass loss (g)	Av. Total gross sweat loss based on mass loss ($g.m^{-2}.h^{-1}$)	HR at 25 min (bpm)	HR at 55 min (bpm)	Av Treadmill speed intensity 1 ($km\,h^{-1}$)	Av. Treadmill speed intensity 2 ($km.h^{-1}$)
m1	21	176 0	70 81	1 88	5 8	62 7	1032	445	136	158	8 5	11 2
m2	21	174 0	70 34	1 84	5 8	93 6	1391	605	135	155	13 9	17 0
m3	23	176 0	68 79	1 86	10 5	88 5	1492	655	135	161	12 5	15 4
m4	28	176 0	71 07	1 86	18 8	60 0	830	358	133	152	8 1	11 7
m6	23	184 5	74 62	1 98	8 3	57 8	1033	422	136	161	8 5	11 9
m7	20	178 0	76 88	1 95	12 2	59 3	1001	414	137	156	9 0	11 2
m8	21	186 0	75 90	2 01	9 6	71 3	1319	528	132	157	12 2	16 2
m9	29	181 5	83 66	2 07	18 8	67 6	1280	501	134	159	9 8	13 5
m10	22	175 0	68 27	1 82	8 3	80 3	1073	474	131	156	11 1	14 2
mean ± SD	**23 ± 3**	**178 6 ± 4.4**	***73 4 ± 4 9***	**1.90 ± 0 1**	**10 9 ± 4 9**	**71.2 ± 13**	***1161 ± 217***	***489 ± 95***	**134 ± 2**	**157 ± 3**	***10 4 ± 2.1***	***13.6 ± 2 2***

Table 4.2. Participant characteristics for head and face sweat mapping

Participant no	Age (yrs)	Height (cm)	Weight (kg)	Surface area (m^2)	Body Fat (%)	Predicted $VO_{2\ max}$ ($ml.kg^{-1}\ min^{-1}$)	Av. Total gross sweat loss based on mass loss (g)	Av. Total gross sweat loss based on mass loss ($g\ m^{-2}.h^{-1}$)	HR at 25 min (bpm)	HR at 55 min (bpm)	Av. Treadmill speed intensity 1 ($km\ h^{-1}$)	Av. Treadmill speed intensity 2 ($km.h^{-1}$)
m4	30	176 0	68 79	1 86	18 8	60 0	781	360	129	150	8 3	11 6
m6	24	184 5	74 62	1 98	8 3	57 8	917	397	135	160	9 6	13 1
m7	21	178 0	76 88	1 95	12 2	59 3	968	424	133	160	9 5	11 0
m9	30	181 5	83 66	2 07	18 8	67 6	1028	427	133	160	11 0	14 5
m11	21	178 0	72 00	1 89	7 1	79 6	1036	469	133	155	11 6	14 3
m12	28	177 5	74 17	1 92	10 5	51 5	812	363	142	160	6 8	9 0
m13	21	186 4	62 81	1 85	7 1	52 7	476	221	136	159	6 5	9 0
m14	21	187 5	73 48	1 98	8 8	51 4	908	392	134	164	7 8	11 0
m15	22	184 6	76 02	1 99	14 8	41 0	536	231	135	170	6 0	9 8
mean ± SD	**24 ± 4**	**181 6 ± 4.3**	**73 60 ± 5.7**	**1 94 ± 0 1**	**11 8 ± 4 7**	**57.9 ± 11**	**829 ± 203**	**365 ± 86**	**134 ± 4**	**160 ± 4**	**8 6 ± 2 0**	**11 5 ± 2 1**

4.3.3 Core Temperature

During all experiments some data points were missing due to the telemetry monitor failing to receive a signal from the core temperature pill. Results are therefore presented as the mean T_{core} over the final 5 minutes of I1 and I2, where all data was available. Baseline data was taken as the temperature recorded immediately before commencing I1.

4.3.3.1 Body Mapping

Mean T_{core}, heart rate and work rate for each exercise intensity during the body mapping experiments are presented in Table 4.3.

Table 4.3. Mean core temperature, heart rate, and work rate (± SD) at different exercise intensities *** denotes significance at the p<0 001 from the previous time point

Time point	Tcore (°C)	Heart rate (bpm)	Work rate (%$VO_{2\ max}$)
baseline	36 93 ± 0.39	59 ± 9	-
I1 (26-30)	37.68 ± 0 43***	134 ± 3***	54 ± 4***
I2 (56-60)	38 06 ± 0 42***	157 ± 4***	73 ± 7***

T_{core} increased significantly from *BL* to I1 (p<0 001) and from I1 to I2 (p<0 001). In all participants T_{core} was higher at I2 compared with I1 in addition to both work rate (% $VO_{2\ max}$) and heart rate being significantly higher at I2 (p<0.001) than I1. Sublingual temperature (mean of all experiments) increased significantly during the testing (p < 0.05) from 36.4 ± 0 2°C to 36.8 ± 0 1°C

Participant m10 was requested to ingest a core temperature pill for all sessions to assess intra individual variability in T_{core}. Mean values of 36 45 ± 0.2°C, 37 10 ± 0 3°C, and 37 57 ± 0 2°C were observed for baseline, I1, and I2 respectively.

4.3.3.2 Head, Face and Neck

Mean T_{core}, heart rate and work rate (% $VO_{2\ max}$) for each exercise intensity during the body mapping experiments is presented in Table 4.4.

Table 4.4. Mean core temperature, heart rate, and work rate (± SD) at different exercise intensities Significance from the previous time point is denoted by *** at the p<0 001, ** at the p<0 01 level, and * at the p<0 05 level

Time point	Tcore (°C)	Heart rate (bpm)	Work rate (%$VO_{2\ max}$)
baseline	37 23 ± 0 32	75 ± 19	-
End I1 (26-30)	37.79 ± 0.15**	134 ± 4***	54 ± 4
End I2 (56-60)	38 17 ± 0.07*	160 ± 4***	72 ± 8***

T_{core} increased significantly from baseline to I1 (p<0.01) and from I1 to I2 (p<0 05). In all participants T_{core} was higher at I2 compared with I1 in addition to both work rate (% $VO_{2\ max}$) and heart rate being significantly higher at I2 (p<0 001) than I1 Sublingual temperature increased from 36 9 ± 0 4°C to 37.2 ± 0.4°C from *BL* to the end of testing, which was close to significance (p = 0 053). No significant differences were present in T_{core} between body mapping and head and face participants at baseline or either exercise intensity. Heart rate was significantly higher at baseline (p<0 05) in head and face participants compared to body mapping, however no significant differences were present in heart rate or work rate at either exercise intensity between groups.

4.3.4 Gross Sweat Loss

GSL was calculated for all body mapping and head, face and neck experiments from the total weight change of each participant and adjusted for fluid consumption. *GSL* was corrected for respiratory and metabolic losses (Chapter 2 equations 2.8 to 2.12)

4.3.4.1 Body Mapping

Corrected (metabolic and respiratory losses) and uncorrected values for *GSL* from all body mapping experiments are presented in grams per surface area ($g\ m^{-2}.h^{-1}$) for each participant (Table 4.5). Unless otherwise stated, corrected values for *GSL* were used in analysis and discussion.

Considerable variation in *GSL* was observed both within sessions and between individuals *GSL* during the upper body experiment was significantly higher ($p<0.05$) than during the legs test. The mean (± SD) difference between all experiments for all participants (corrected *GSL*) was 77 ± 60 $g.m^{-2}.h^{-1}$ with a range from 8 to 203 $g\ m^{-2}\ h^{-1}$ between individuals Similarly, large variation was observed between individuals with values ranging from 358 ± 67 to 655 ± 86 $g\ m^{-2}\ h^{-1}$ for participants m4 and m3 respectively. The mean (± SD) sweat loss of all experiments was calculated for both exercise intensities (Table 4.6). Corrected and uncorrected values are presented in grams (g) and grams per surface area ($g\ m^{-2}\ h^{-1}$) for each participant. *SA* weighted values are presented from the sum of all regional area weighted sweat rates (all pads) *GSL* increased significantly ($p<0.001$) with exercise intensity with an average increase over all experiments of 302 ± 96 $g\ m^{-2}\ h^{-1}$ between I1 and I2 Large variation was observed between individuals, ranging from differences of 93 to 437 $g\ m^{-2}\ h^{-1}$ between exercise intensities. A significant difference was similarly present between exercise intensities for *SA* weighted *SR* ($p < 0.001$) A significant difference was present between *GSL* calculated from weight change and *SA* weighted *SR* at both intensities (I1 $p < 0.01$, I2 $p < 0.001$)

Table 4.5. Gross sweat loss (g m^{-2} h^{-1}) uncorrected (uc) and corrected (c) for respiratory and metabolic mass loss during all body mapping experiments AHGF arms, hands, gluts (buttocks), and feet experiment, UB upper body experiment, Legs – legs experiment * denotes a value significantly higher than the legs at the p<0 05 level

	AHGF		UB		Legs		mean		median		SD	
Participant	**uc**	**c**	**un**	**c**	**uc**	**c**	**uc**	**c**	**uc**	**c**	**uc**	**c**
m1	469	396	656	572	452	368	526	445	469	396	113	110
m2	721	588	805	671	694	557	740	605	721	588	58	59
m3	846	725	791	680	675	559	770	655	791	680	87	86
m4	458	372	500	417	364	285	441	358	458	372	70	67
m6	520	438	550	468	440	360	503	422	520	438	57	56
m7	474	389	512	431	505	423	497	414	505	423	20	22
m8	629	511	501	522	664	551	598	528	629	522	86	21
m9	715	615	572	452	533	437	607	501	572	452	96	99
m10	562	454	609	505	569	465	580	474	569	465	26	27
mean	**599**	**499**	**611***	**524***	**544**	**445**						
median	**562**	**454**	**572**	**505**	**533**	**437**	***585***	***489***	***562***	***465***	***123***	***107***
SD	**137**	**121**	**118**	**98**	**116**	**98**						

Table 4.6. Mean gross sweat loss from all body mapping experiments uncorrected (uc) and corrected (c) for respiratory and metabolic mass loss at I1 and I2 Whole body surface area weighted sweat rate for all regions measured with pads are presented for I1 and I2 *** denotes significance at the p<0 001 level between I1 and I2

	Gross sweat loss I1 (g)		Gross sweat loss I2 (g)		Gross sweat loss I1 ($g.m^{-2}.h^{-1}$)		Gross sweat loss I2 ($g.m^{-2}.h^{-1}$)		SA weighted SR I1 ($g.m^{-2}.h^{-1}$)	SA weighted SR I2 ($g.m^{-2}.h^{-1}$)
Participant	**uc**	**c**	**uc**	**c**	**uc**	**c**	**uc**	**c**		
m1	432	355	722	623	344	283	768	662	247	364
m2	719	596	873	707	585	484	946	767	433	520
m3	710	602	957	815	574	487	1032	879	456	614
m4	405	331	569	464	327	267	613	500	190	291
m6	527	449	636	527	399	340	642	532	186	295
m7	433	349	700	595	333	268	716	609	229	338
m8	615	502	894	733	460	375	891	731	286	466
m9	642	546	801	661	466	397	776	640	275	419
m10	558	463	670	542	461	382	738	597	207	372
mean ± SD	***560 ± 120******	***466 ± 105******	***758 ± 130******	***630 ± 111******	***439 ± 97******	***365 ± 84******	***791 ± 139******	***657 ± 119******	**279 ± 100***	**409 ± 108***

4.3.4.1.1 Gross Sweat Loss and Predicted Maximal Oxygen Uptake

GSL over the whole test period (mean of all body mapping experiments) was plotted against predicted $VO_{2\,max}$ for all participants and a regression line fitted (Figure 4 4).

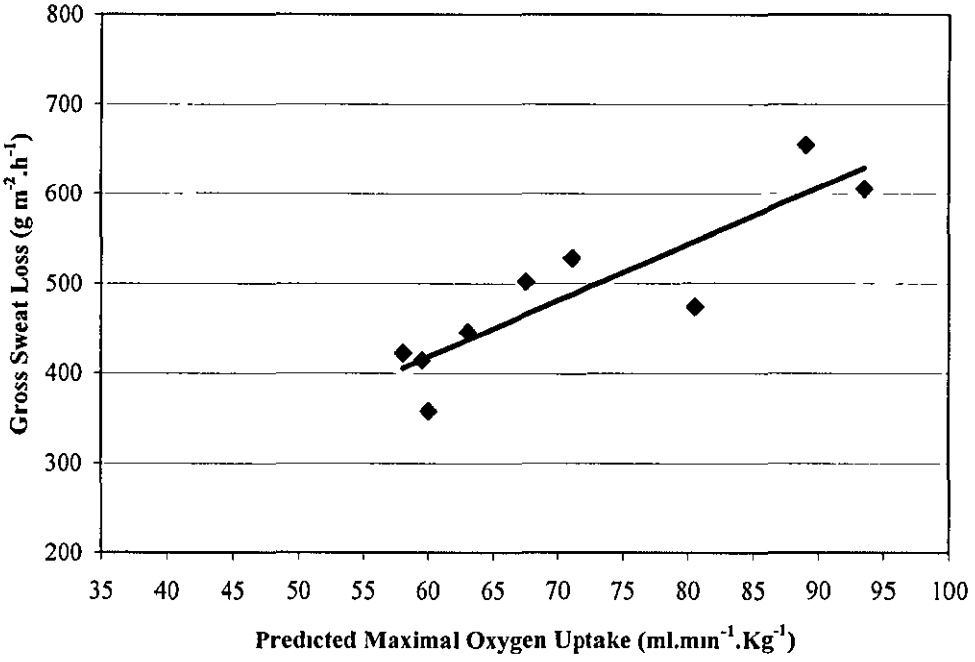


Figure 4.4 Gross sweat loss and predicted $VO_{2\,max}$ for all body mapping participants

A Pearson's r correlation coefficient of 0 88 indicates a significant ($p<0\ 001$) positive correlation between *GSL* and $VO_{2\,max}$ in male athletes for the experimental conditions used.

4.3.4.1.2 Gross Sweat Loss and Core Temperature

Mean *GSL* from all experiments was plotted against mean T_{core} from I1 and I2 for all participants (Figure 4.5).

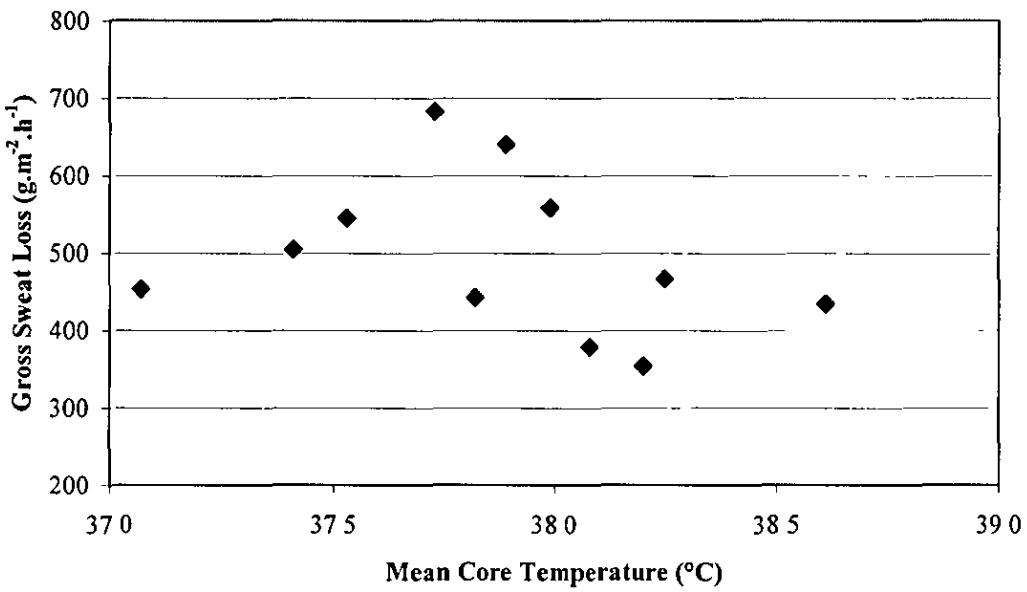


Figure 4.5. Mean gross sweat loss (g m^{-2} h^{-1}) of all experiments and mean core temperature

A Pearson's r correlation coefficient of -0 07 indicates no correlation between mean *GSL* and mean T_{core} in male athletes in the present experimental conditions.

4.3.4.2 Head Face and Neck

Corrected and uncorrected values for *GSL* of the head, face and neck are presented in Table 4.7. Values are presented in grams (g) and grams per surface area (g m^{-2} h^{-1}) at I1 and I2 for each participant. *SA* weighted values are presented from the sum of all regional area weighted sweat rates (all pads) Shading denotes participants involved in sweat mapping of the head as opposed to those involved in sweat mapping of the face and neck only. Unless otherwise stated, corrected values for *GSL* will be used in analysis and discussion

Table 4.7. Gross sweat loss at I1 and I2, and sum of surface area weighted sweat rate of all pads Shading (▭) denotes participants involved in head sweat mapping

	Gross sweat loss I1(g)		Gross sweat loss I2 (g)		Gross sweat loss I1 ($g.m^{-2}.h^{-1}$)		Gross sweat loss I2 ($g\ m^{-2}.h^{-1}$)		SA weighted SR I1 ($g.m^{-2}.h^{-1}$)	SA weighted SR I2 ($g.m^{-2}.h^{-1}$)
Participant	**uc**	**c**	**uc**	**c**	**uc**	**c**	**uc**	**c**		
m4	332	258	624	523	268	208	672	563	207	396
m6	524	437	604	481	397	331	610	485	331	682
m7	434	347	723	621	333	266	740	635	285	587
m9	501	399	770	628	364	290	746	609	336	609
m11	493	390	796	662	390	309	841	699	277	536
m12	420	353	543	460	328	276	566	479	307	461
m13	243	181	371	294	197	147	402	318	82	183
m14	474	401	607	507	359	303	612	511	138	343
m15	280	217	410	319	211	163	412	321	49	382
mean ± SD	**411 ± 102**	**331 ± 91**	**605 ± 148*** **	**499 ± 130*** **	**316 ± 74**	**255 ± 66**	**622 ± 148*** **	**513 ± 131*** **	**224 ± 109**	**464 ± 156*** **

GSL and the sum of *SA* weighted sweat rate increased significantly ($p<0.001$) from I1 to I2. Considerable variation in *GSL* was observed between participants, with values for individuals ranging from 163 to 331 g m^{-2} h^{-1} for I1 and 318 to 699 g $m^{-2}.h^{-1}$ for I2. Similarly, the sum of *SA* weighted *SR* from the head, face and neck showed variation of 49 to 336 g m^{-2} h^{-1} and 183 to 682 g.m^{-2} h^{-1} for I1 and I2 respectively. The mean increase in *GSL* between exercise intensities was 295 ± 98 g m^{-2} h-1, with individual values ranging from 155 to 391 g.m^{-2} h^{-1}.

4.3.4.2.1 Gross Sweat loss and Predicted Maximal Oxygen Uptake

GSL over the whole test period was plotted against predicted $VO_{2\ max}$ for all participants and a regression line fitted (Figure 4.6). A Pearson's r correlation coefficient of 0.77 indicates a strong, significant ($p<0.05$) positive correlation between *GSL* and $VO_{2\ max}$ in the male head, face and neck participants for the experimental conditions used.

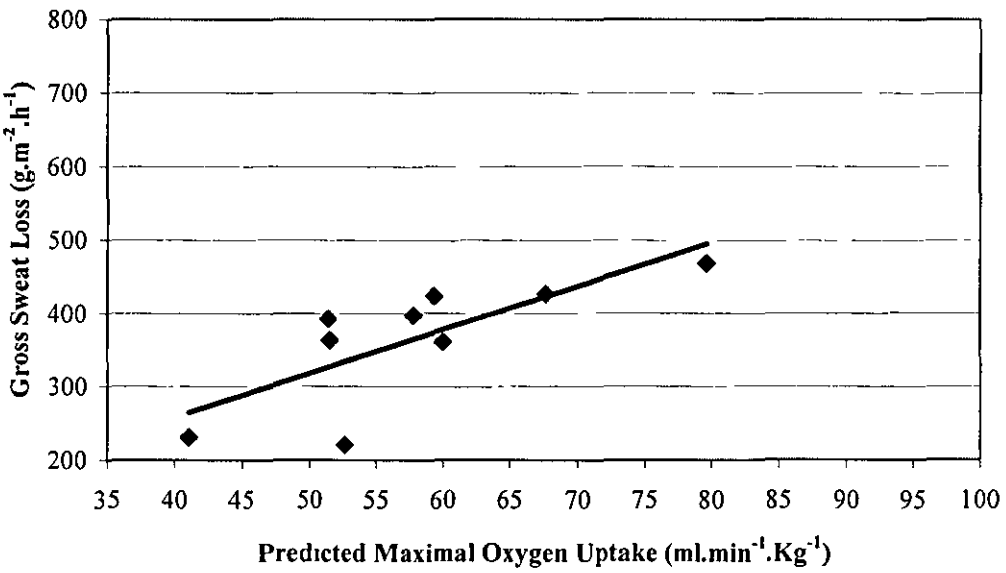


Figure 4.6. Gross sweat loss and predicted $VO_{2\ max}$ for head, face and neck participants

4.3.4.2.2 Gross Sweat Loss and Core Temperature

GSL over the whole experiment was plotted against mean T_{core} from I1 and I2 for all participants except m11 and m13 (Figure 4.7), who did not provide informed consent for radio pill ingestion

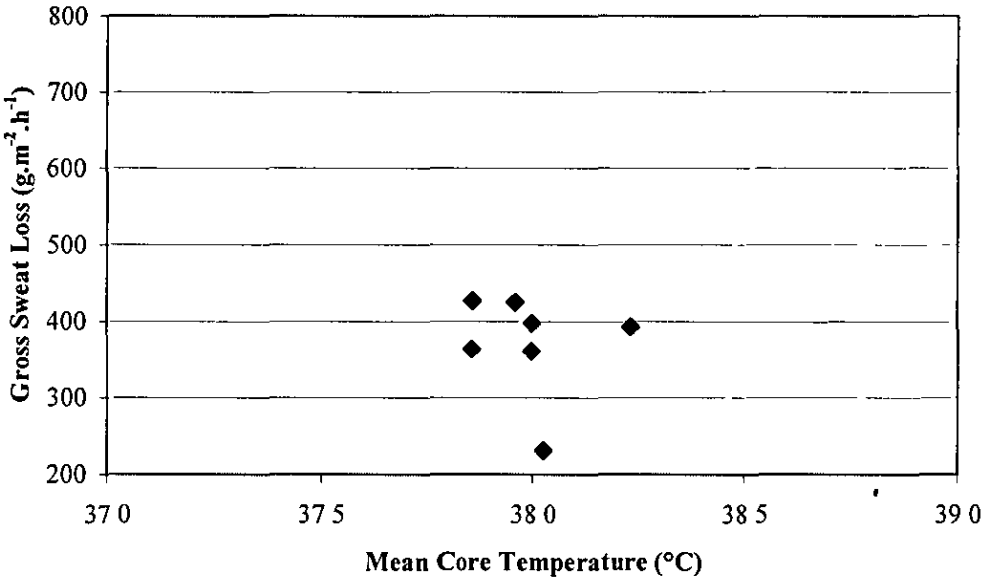


Figure 4.7. Gross Sweat Loss and Mean Core Temperature for head, face and neck participants

A Pearson's r correlation coefficient of -0 02 indicates no correlation between *GSL* and T_{core} in the environmental conditions used

4.3.5 Regional Sweat Rate

4.3.5.1 Body Mapping

Regional *SR* data were analysed for differences in corresponding right-left zones. Paired t-tests were performed on all relevant zones and Bonferroni correction was applied to adjust for multiple comparisons. A small number of right-left zones were significantly different at the 0 05 level of significance, however, these differences tended not to be consistent across exercise intensities nor apparent following Bonferroni correction. At I1 significant right-left differences (without Bonferroni correction) were observed at the shoulders ($p<0$ 05), anterior upper legs ($p<0.05$), anterior lower arms ($p<0.05$), and dorsal hand ($p<0$ 05) With exception only to the shoulders, values were higher on the right side, however no significant differences were present following

correction for multiple comparisons. At I2 significant right-left differences were present at the anterior medial lower leg ($p<0.01$), anterior upper arm ($p<0.05$), and anterior lower arm ($p<0.05$) with all values being greater on the right side. Following Bonferroni correction a significant difference was still present at the anterior medial leg ($p<0.01$). It was decided to group regional *SR* data for right and left corresponding zones for all analysis since these differences represented a small number of the 70 individual zones sampled over the body. Median right-left grouped data for all participants is illustrated for both exercise intensities in Figure 4.8 and Figure 4.9 respectively.

A number of patterns in regional *SR* were observed in the majority of participants:

- Increase in gross and regional *SR* with exercise intensity
- Posterior torso showed the highest sweat rates over the body at both I1 and I2.
- Feet and ankles showed little increase in sweat rate from I1 to I2
- *SR*s tended to be higher on the dorsal compared to the plantar surface of the feet in both I1 and I2, and similarly higher on the dorsal compared to ventral surface of the hands
- Hands and fingers show little increase with exercise intensity
- A medial to lateral decrease in *SR* across the torso.
- Few significant right-left differences in corresponding zones
- Increase from proximal to distal regions on the arms.

Regional *SR* was normalised for the area weighed median *SR* of all zones for each individual and then a median of all individuals was taken. Normalised *SR* allowed standardisation of data over participants and allowed easy identification of 'high' and 'low' sweat regions. Normalised sweat data for I1 and I2 are illustrated in Figure 4.10 and Figure 4.11 respectively. The low *SR*s of the extremities compared to the torso are clearly present with little change in distribution from I1 to I2. The medial to lateral decrease across the torso is equally clear, particularly on the posterior. In the absolute sweat data, anterior medial to lateral mid regions (centre anterior mid to sides) decreased by 145 ± 107 g m^{-2} h^{-1} and 219 ± 115 g m^{-2} h^{-1} at I1 and I2 respectively, with only participant m1 showing an increase of 18 g $m^{-2}.h^{-1}$ at I1. Posterior medial to lateral

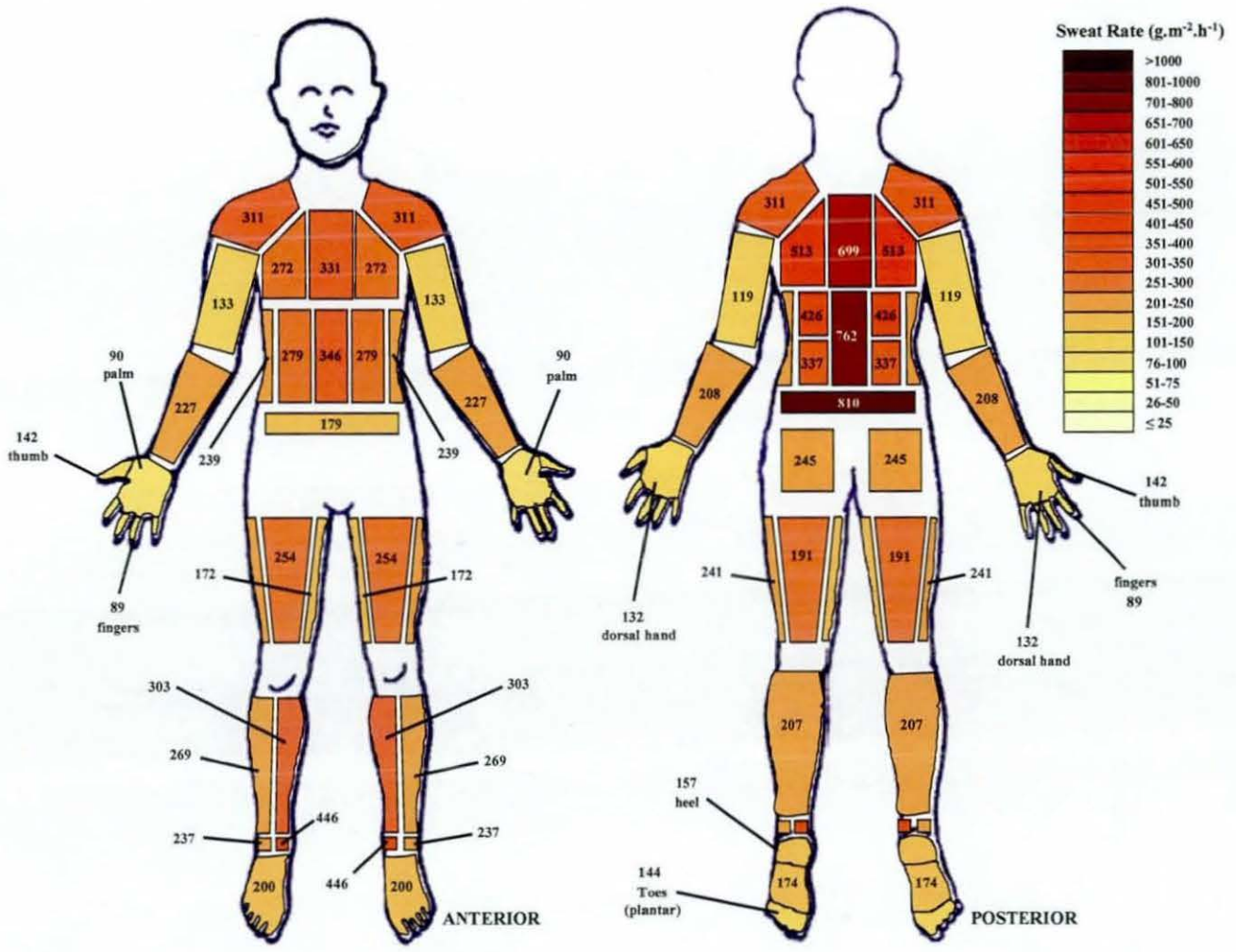


Figure 4.8. Median absolute sweat rate data ($g.m^{-2}.h^{-1}$) for I1.

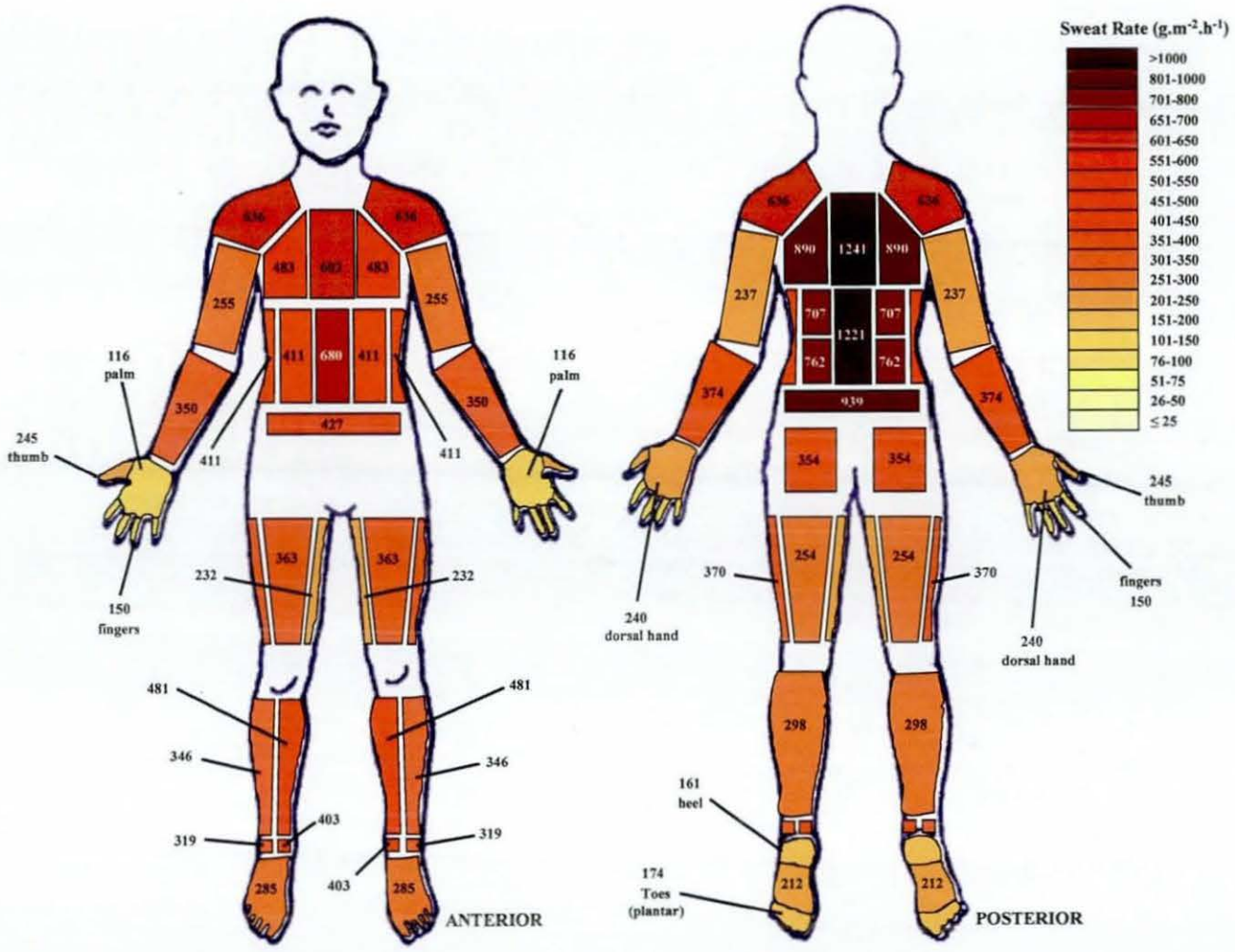


Figure 4.9. Median absolute sweat rate data ($g.m^{-2}.h^{-1}$) for I2.

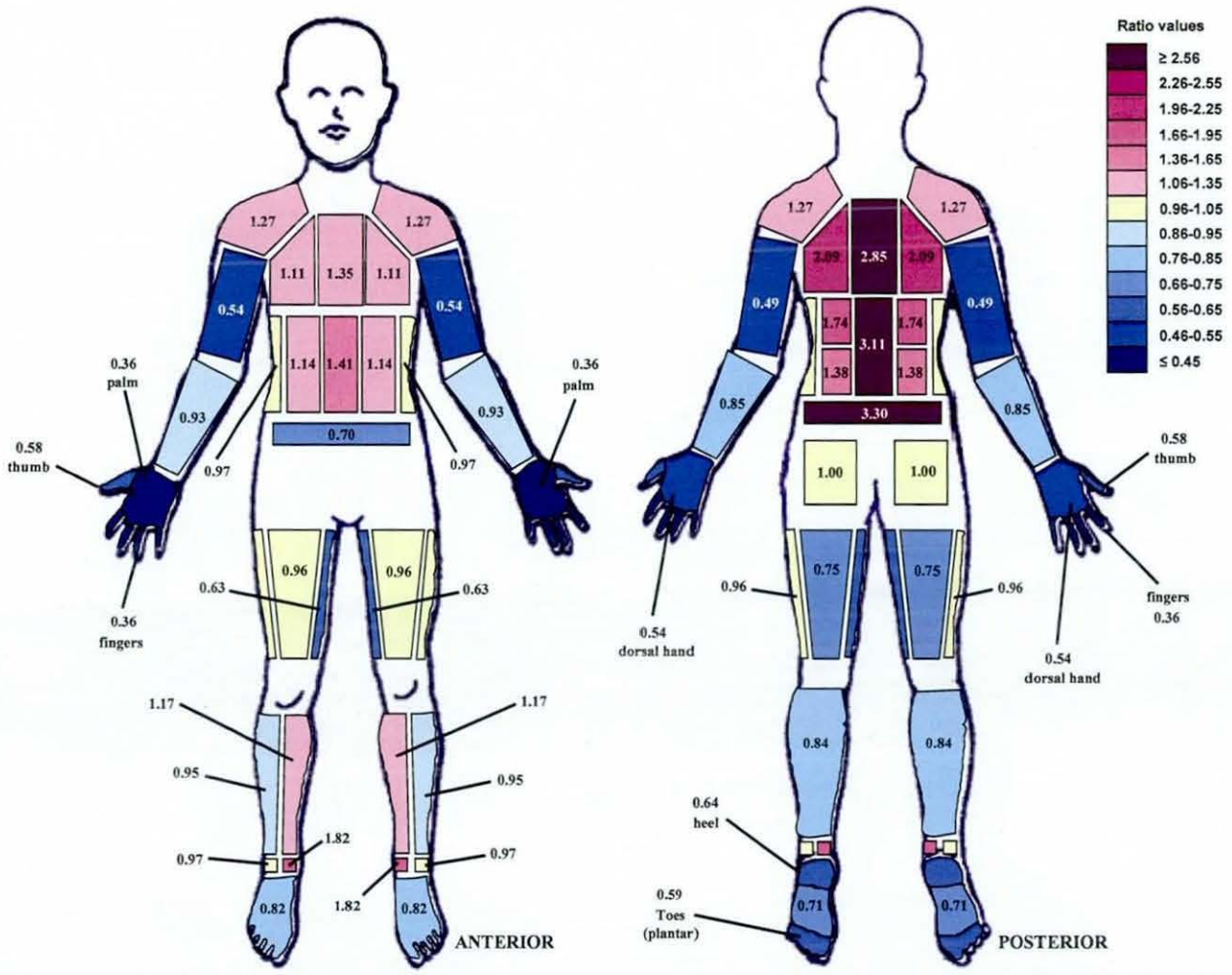


Figure 4.10. Normalised median sweat rate data for I1. A value of 1 indicates a sweat rate equal to the area weighted median sweat rate of all regions measured. Values above or below 1 indicate sweat rates higher or lower than the area weighted median sweat rate of all regions measured respectively.

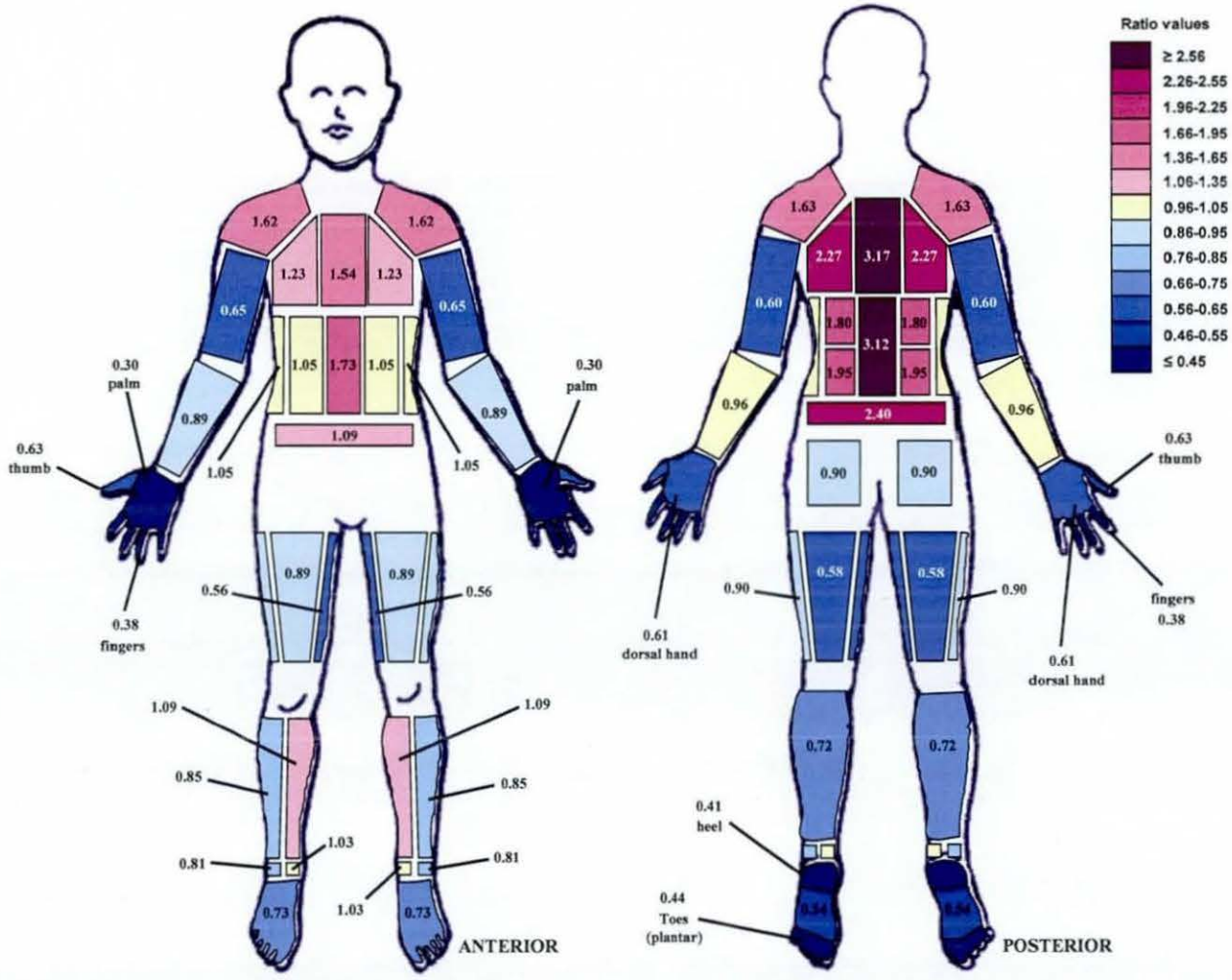


Figure 4.11. Normalised median sweat rate data for I2. A value of 1 indicates a sweat rate equal to the area weighted median sweat rate of all regions measured. Values above or below 1 indicate sweat rates higher or lower than the area weighted median sweat rate of all regions measured respectively.

mid regions (centre posterior mid to sides) decreased by 591 ± 273 $g.m^{-2}.h^{-1}$ and 741 ± 344 $g\ m^{-2}.h^{-1}$ at I1 and I2 respectively.

A comparison of *SR* s within each region from I1 to I2 was performed using a series of paired t-tests and corrected for multiple comparisons (Table 4.8) Data is presented both with and without Bonferroni correction and states descriptive statistics for all regions tested

Table 4.8. Descriptive statistics for all regions sampled at I1 and I2 in male athletes A comparison of sweat rates within each region between exercise intensities for both absolute and normalised data, corrected and uncorrected for multiple comparisons A decrease in median sweat rate between intensities is indicated by grey shading (not shown)

	Absolute sweat data ($g\ m^{-2}\ h^{-1}$)										Significance level of intensity comparison	
	I1					I2						
	min	max	median	mean	SD	min	max	median	mean	SD	Absolute data	Normalised ratio data
shoulders	236	591	311	345	119	403	941	636	660	199	***###	**
lat upper chest	138	490	272	271	105	342	940	483	510	181	***###	**$
centre ant upper	172	586	331	342	145	350	1046	602	641	253	***###	**$
lat mid chest	203	479	279	293	82	238	736	411	461	145	**$	-
centre ant mid	177	823	346	409	185	268	1000	680	692	239	**$	-
sides	108	552	239	264	126	233	755	411	473	172	***#	*
ant lower	30	405	173	185	119	99	688	426	392	197	**	*
lat pos upper	426	970	513	591	196	666	1346	890	881	232	***##	-
centre pos upper	492	1148	699	751	239	617	1515	1241	1116	321	***##	-
lat pos M-U	151	653	426	421	157	337	927	707	665	194	***###	-
lat pos M-L	252	785	337	394	171	312	1065	762	693	252	**$	-
centre pos mid	537	1338	762	854	269	681	1647	1221	1214	351	**$	-
pos lower	324	1819	810	802	459	415	2175	939	1035	535	-	-
ant upper leg	119	417	235	240	96	206	518	348	340	109	***###	-
med upper leg	83	330	154	172	81	147	455	219	241	99	***##	-
pos upper leg	105	270	183	181	54	139	365	229	240	75	**$	-
lat upper leg	120	492	235	279	131	111	623	352	348	147	**$	**
ant lat lower leg	137	609	232	303	180	206	792	331	383	175	*	-
ant med lower leg	141	699	286	349	202	235	842	427	444	185	**	-
pos lower leg	115	406	206	225	88	157	533	282	293	110	***#	*
ant upper arm	68	354	133	150	91	127	512	255	265	107	***##	**
pos upper arm	28	410	119	153	119	92	577	237	266	133	***###	**
ant lower arm	94	547	227	244	152	220	472	350	366	91	**	-
pos lower arm	95	632	208	262	175	196	713	374	402	154	**$	-
thumbs	90	295	142	184	86	146	358	245	244	77	**$	-
fingers	55	224	89	118	65	80	206	150	154	46	**	-
palms	37	211	90	99	59	56	219	116	127	53	*	-
dorsal hand	67	376	132	168	98	132	336	240	236	69	*	-
gluts	103	425	245	265	118	206	683	354	368	140	*	-
sole	102	400	174	202	96	132	356	212	225	79	-	**
dorsal foot	117	511	200	271	142	158	564	285	314	129	-	*
toes	104	242	144	162	44	127	228	174	174	36	-	**
heel	93	240	157	165	49	143	275	161	179	44	-	**$
med ankles	165	813	446	428	241	151	839	403	441	223	-	*
lat ankles	69	724	237	267	208	108	413	319	251	122	-	-

For conversion to other units divide by 600 to get mg cm^{-2} min^{-1}, or by 10,000 to get ml cm^{-2} h^{-1}
No correction *P ? 0 05, **P ? 0 01, ***P ? 0 001,
Bonferroni correction # P ? 0 05, ## P ? 0 05, ### P ? 0 001, $ 0 1 > P ? 0 05

The large variation between participants is clearly evident from the minimum and maximum values within each region Notably, the mean is higher than the median in 30 out of 35 regions, indicating a slightly skewed distribution with occasional outliers

typically towards the higher *SR* s. This reinforces the value of using median data in *SR* analysis When considering absolute regional *SR* s between exercise intensities, most regions exhibited a significant increase. Interestingly, the hands, feet and ankles showed no increase. The normalised data indicates little change in regional distribution with exception to a significant decrease in relative *SR* over the feet. When corrected for multiple comparisons no significant differences were present in the normalised data, indicating no redistribution towards a more unified sweat rate with exercise intensity under the present experimental conditions

Due to the exploratory nature of the sweat mapping study it was decided to perform a comparison of all regions within each exercise intensity. The design was treated as repeated measures since each measurement was performed on the same individual Each region is not strictly repeated measures since different areas (variables) are measured, yet nor are they independent from each other when measuring multiple regions on the same individual On balance, it was decided to use a repeated measures ANOVA to allow regional comparison, with adjustment for multiple comparisons. Data is presented both with and without Bonferroni correction due to the exploratory nature of the study and the conservative nature of the Bonferroni correction Table 4 9 and Table 4 10 show the significance level of the comparison between all regions in II with and without Bonferroni correction respectively

Table 4.9. Significance levels of comparison of absolute sweat rates for all regions at 11 uncorrected for multiple comparisons

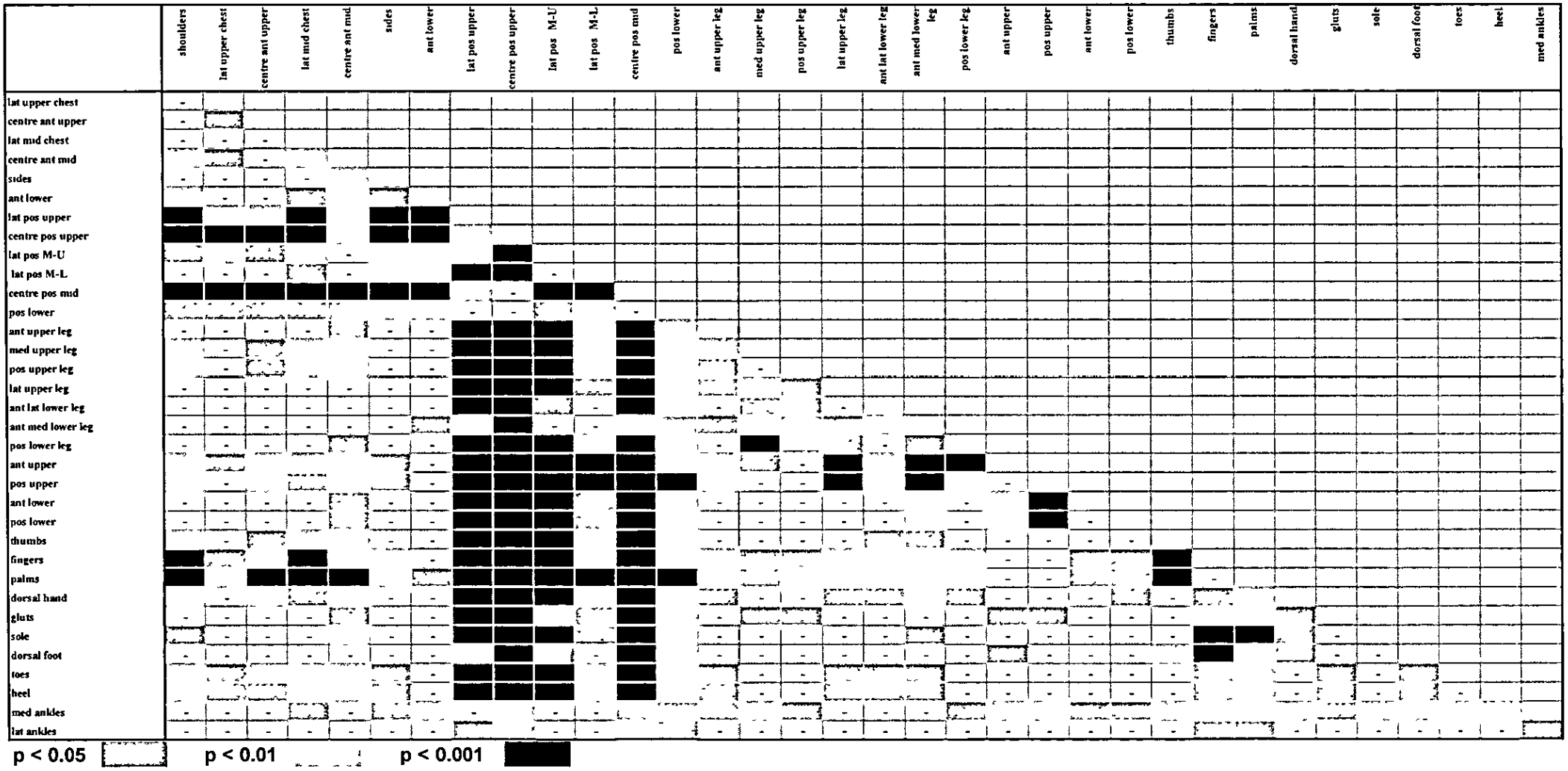


Table 4.10. Significance levels of comparison of absolute sweat rates for all regions at 11 after Bonferroni correction

	shoulders	lat upper chest	centre ant upper	lat mid chest	centre ant mid	sides	ant lower	lat pos upper	centre pos upper	lat pos M-U	lat pos M-L	centre pos mid	pos lower	ant upper leg	med upper leg	pos upper leg	lat upper leg	ant lat lower leg	ant med lower leg	pos lower leg	ant upper	pos upper	ant lower	pos lower	thumbs	fingers	palms	dorsal hand	gluts	sole	dorsal foot	toes	heel	med ankles
lat upper chest	-																																	
centre ant upper	-	-																																
lat mid chest	-	-	-																															
centre ant mid	-	-	-																															
sides	-		-		-																													
ant lower	-		-			-																												
lat pos upper	-	-	-	-		-	-																											
centre pos upper	-	-	-	-		-	-	-																										
lat pos M-U	-	-	-	-	-	-	-	-	$																									
lat pos M-L	-	-	-	-	-	-	-	-	-	-																								
centre pos mid	-	-	-	-	-	-	$	-		-	-																							
pos lower	-	-		-	-	-	-	-		-	-																							
ant upper leg	-	-			-	-	-	-		-	-	-																						
med upper leg	-		-		-	-	-				-	$																						
pos upper leg	-					-	-	-		$	-	$																						
lat upper leg	-	-	-			-	-	-		-	-	-	-	-	-	-																		
ant lat lower leg	-		-		-	-	-	-		-	-	-	-	-		-	-																	
ant med lower leg	-	-	-	-	-		-	-	$	-		-		-	-	-	-	-																
pos lower leg	-	-	-	-	-	-	-	$			-	$	-	-	-	-	-	-	-															
ant upper	-	-	-	-	-	-	-						-	-	-	-	-	-																
pos upper	-	-	-	-	-	-	-				-		-	-	-	-	-	-		-	-													
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palms			-	-	-	-	-	$			-		-	-	-	-	-	-	-	-	-	-	-	-	-	-								
dorsal hand	-		-		-	-	-	$	$		-			-		-		-	-	-	-	-	-	-	-	-	-							
gluts	-	-	-	-	-				-	-	-			-	-	-		-	-	-	-	-	-	-	-	-	-	-						
sole	-	-	-	-	-	-	-	-	-		-		-	-	-	-		-	-			-	-	-	-	-	-	-	-					
dorsal foot		-	-	-	-	-	-	-	-		-		-	-	-	-	-	-				-	-	-		-	-	-		-				
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$p < 0.05$ $p < 0.01$ $0.1 < p \geq 0\ 05$ $

Table 4.11. Significance levels of comparison of absolute sweat rates for all regions at I2 uncorrected for multiple comparisons

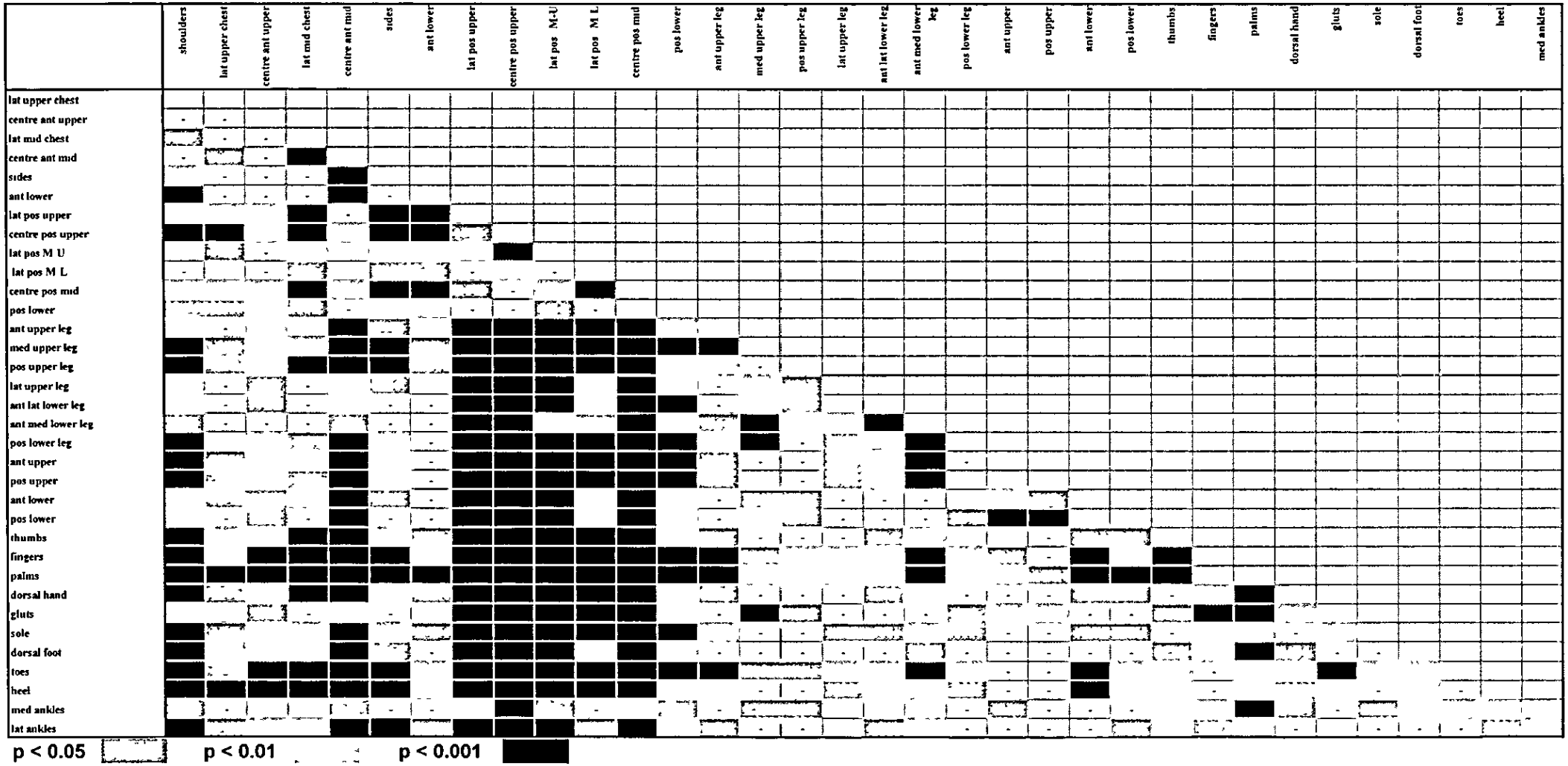

Table 4.12. Significance levels of comparison of absolute sweat rates for all regions at I2 after Bonferroni correction

	shoulders	lat upper chest	centre ant upper	lat mid chest	centre ant mid	sides	ant lower	lat pos upper	centre pos upper	lat pos M-U	lat pos M L	centre pos mid	pos lower	ant upper leg	med upper leg	pos upper leg	lat upper leg	ant lat lower leg	ant med lower leg	pos lower leg	ant upper	pos upper	ant lower	pos lower	thumbs	fingers	palms	dorsal hand	gluts	sole	dorsal foot	toes	heel	med ankles
lat upper chest	-																																
centre ant upper	-																																
lat mid chest	-		-																														
centre ant mid	-		-	-																													
sides	-		-	-	-																												
ant lower	-	-	-	-	$																												
lat pos upper	-	-		-	-	$	-																										
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lat pos M U		-	-	-		-	-	-	-																								
lat pos M L	-	-	-	-	-	-	-	-	-	-																							
centre pos mid	-	-	-	-	-	-	-	-	-	-	-																						
pos lower	-		-	-	-	-	-	-	-	-		-																					
ant upper leg	-	-	-		-	-	-		$	$		$	-																				
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pos upper leg	-	-		-		-					-		-	-	-																		
lat upper leg		-		-	-	-				$	-	$	-	-	-	-																	
ant lat lower leg		-	-	-	-	-	-		$	-	-	$	-	-	-	-																	
ant med lower leg	-	-	-	-	-	-	-		-	-	-		-	-	-	-	-	-															
pos lower leg	-		-	-	-	-	-				-		-	-	-	-	-	-	-														
ant upper	-	-	-	-	-	-	-				-		-	-		-	-		-														
pos upper	-		-	-	-	-	-				$		-	-	-	-	-	-	-	-	-												
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dorsal hand		-	-	-	-	-			$		-		-	-	-	-	-	-	-	-	-		-	-	-	-	-						
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sole	-	-	-	-	-		-		-	$	-		-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-				
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lat ankles	-	-	-		$		-	$	$	-	-	$	-	-	-	-	-	-	-	-	-		-	-	-	-	-		-	-	-	-	-

$p < 0.05$ $p < 0.01$ $p < 0.001$ $0.1 > p \geq 0.05$ $

4.3.5.2 Head, Face and Neck

Regional head, face and neck *SR* data were analysed for differences in left-right and medial-lateral zones. A one-way repeated measures ANOVA with post hoc pairwise comparisons was performed on all relevant zones and Bonferroni correction was applied to adjust for multiple comparisons. The only significant difference present at I1 was between the anterior neck and left lateral posterior head ($p<0.01$). At I2 a number of significant differences were present between zones ($p<0.05$), particularly in comparison to the forehead. All zones except the right and left lateral mid head showed significantly lower *SR* s compared to the forehead. Significant differences were additionally present between the following zones; left cheek and left lateral anterior head ($p<0.05$), chin and right lateral anterior head ($p<0.05$), anterior neck and medial anterior head ($p<0.05$), posterior neck and medial mid head ($p<0.05$), right lateral anterior head and medial mid head ($p<0.01$), and right lateral posterior head and left lateral posterior head ($p<0.05$). No significant differences were present at either exercise intensity following Bonferroni correction. A mixture of right and left zones were significantly higher and on balance it was decided to group *SR* data into forehead, cheeks, chin, medial head, right lateral head and left lateral head for analysis. Median grouped data for all participants are illustrated for exercise intensities one and two in figures Figure 4.12 and Figure 4.13 respectively.

The forehead showed the highest regional SR over both exercise intensities with median values (inter-quartile range (IQR)) of 520 (984) $g.m^{-2}.h^{-1}$ and 1275 (966) $g.m^{-2}.h^{-1}$ respectively. During I1, the right lateral head showed the next highest sweat rate of 237 (IQR 343) $g.m^{-2}.h^{-1}$ followed by the arm with a value of 224 (IQR 138) $g.m^{-2}.h^{-1}$. The lowest values were observed on the face, with the chin and cheeks showing values of 97 (IQR 63) and 63 (IQR 71) $g.m^{-2}.h^{-1}$ respectively. During I2, the right and left lateral head showed the highest values after the forehead, with sweat rates of 565 (416) and 511 (361) $g.m^{-2}.h^{-1}$ respectively. Similarly to I1 the lowest values were observed on the chin and cheeks, with values of 225 (77) and 208 (111) $g.m^{-2}.h^{-1}$ respectively. As with the body mapping data analysis, a repeated measures ANOVA was conducted to allow regional comparison of the grouped data, with adjustment for multiple comparisons. No significant differences were present between regions at I1, with the head being

significantly higher than all other regions at I2 (cheeks $p<0.01$, all other regions $p<0.05$). No significant differences were present following Bonferroni correction.

Regional *SR* data of the head, face and neck was also normalised for the area weighed median *SR* of all measured zones (total number of zones depending on whether the head was measured or only the face and neck) and then an average of all individuals was taken. Since not all of the participants provided head data, normalised ratio values were calculated separately for 1) face and neck experiments (n=9) and 2) head, face and neck (n=4). Normalised sweat data for the face and neck at I1 and I2 are illustrated in Figure 4.14 and Figure 4.15 respectively. Normalised data for at I1 and I2 for the head, face, and neck are illustrated in Figure 4.16 and Figure 4.17. The consistently high *SR* on the forehead during both exercise intensities was evident in both the face and neck, and the head group. The low *SR* of the arms and neck are similarly evident in both groups, with a decreasing relative contribution to overall *SR* with an increase in work rate. The medial to lateral increase on the head, although not significant, decreased towards a more uniform distribution from I1 to I2 as a result of a greater contribution from the medial head to the overall *SR*.

A comparison of each regional *SR* between exercise intensities was performed using paired t-tests, both with and without Bonferroni correction (Table 4.13). Data for the face and neck is presented for all participants with the head, face and neck presented separately due to the differences in the number of regions measured influencing the normalised ratio data. Descriptive statistics are additionally presented, highlighting the individual differences in absolute *SR* both within and between regions. Regardless of this, similarities in distribution were present across the head, face and neck. All regional *SR* s over the face and neck increased significantly with exercise intensity but showed little change in distribution. A significant decrease was present in the ratio value of the arms however this reflects the extremely high *SR* of the forehead raising the area weighted *SR* of all zones. The data from the head participants showed a significant increase in absolute *SR* with exercise intensity in all regions except the cheeks, neck, and medial head. A change in distribution was apparent from I1 to I2 with a significant increase in the normalised ratio values of the chin, cheeks, and left lateral head. No significant differences were present following Bonforroni correction.

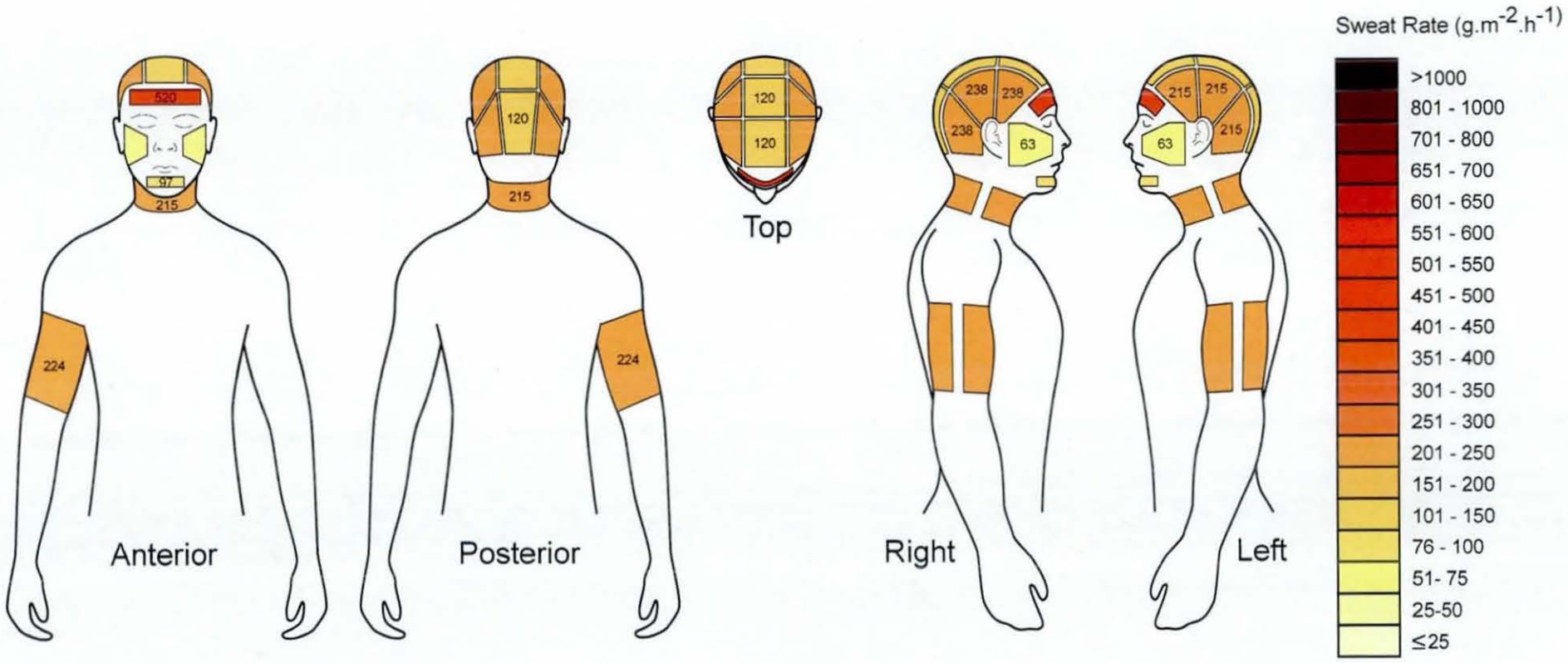


Figure 4.12. Median absolute sweat rate data ($g.m^{-2}.h^{-1}$) of the head, face and neck at I1.

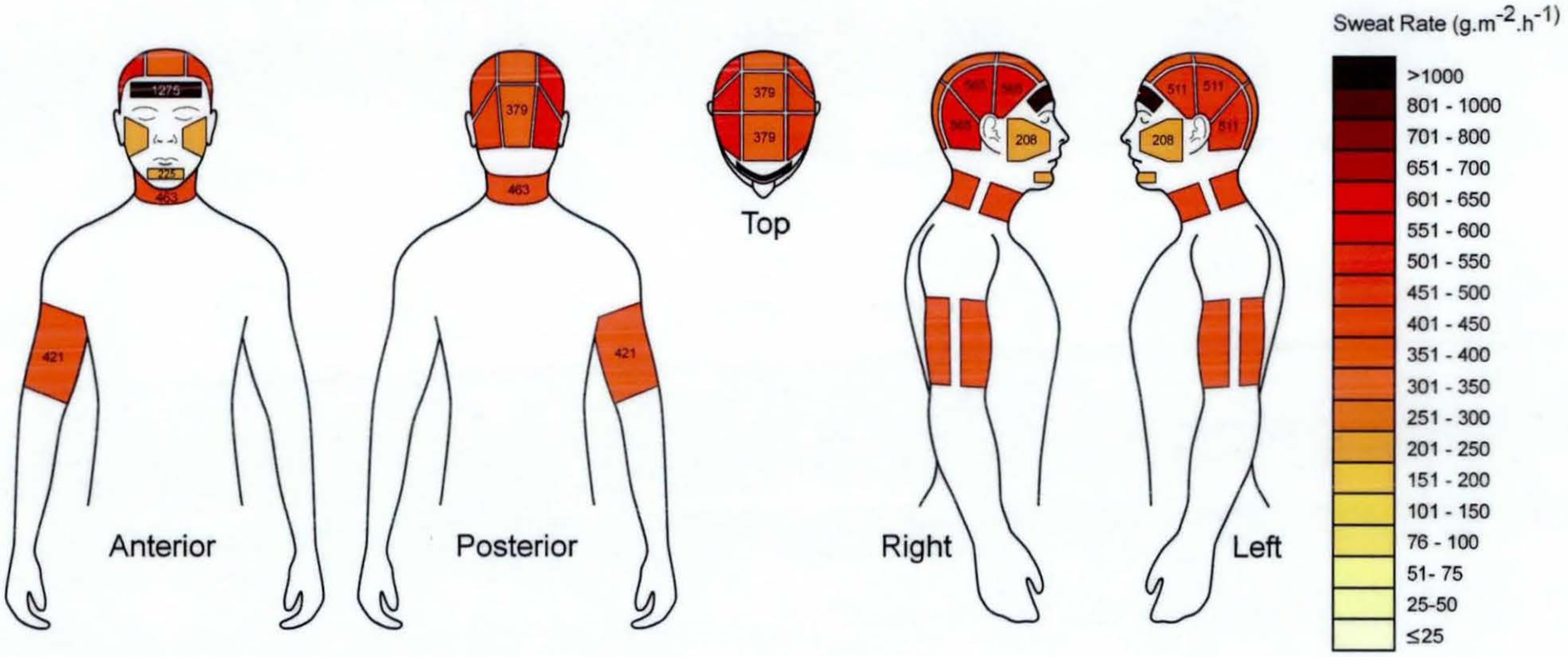


Figure 4.13. Median absolute sweat rate data ($g.m^{-2}.h^{-1}$) of the head, face and neck at I2.

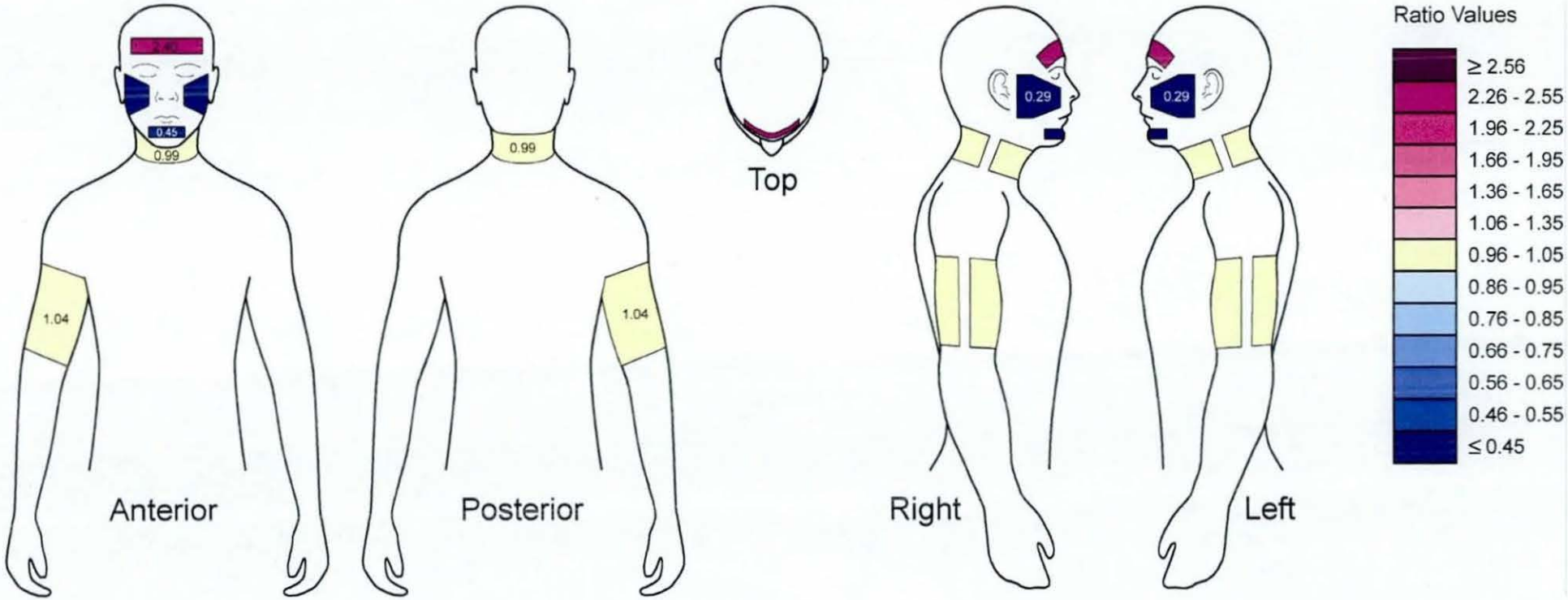


Figure 4.14. Normalised median sweat rate data for the face and neck at I1 (n = 9. A value of 1 indicates a sweat rate equal to the area weighted median sweat rate of all regions measured. Values above or below 1 indicate sweat rates higher or lower than the area weighted median sweat rate of all regions measured respectively.

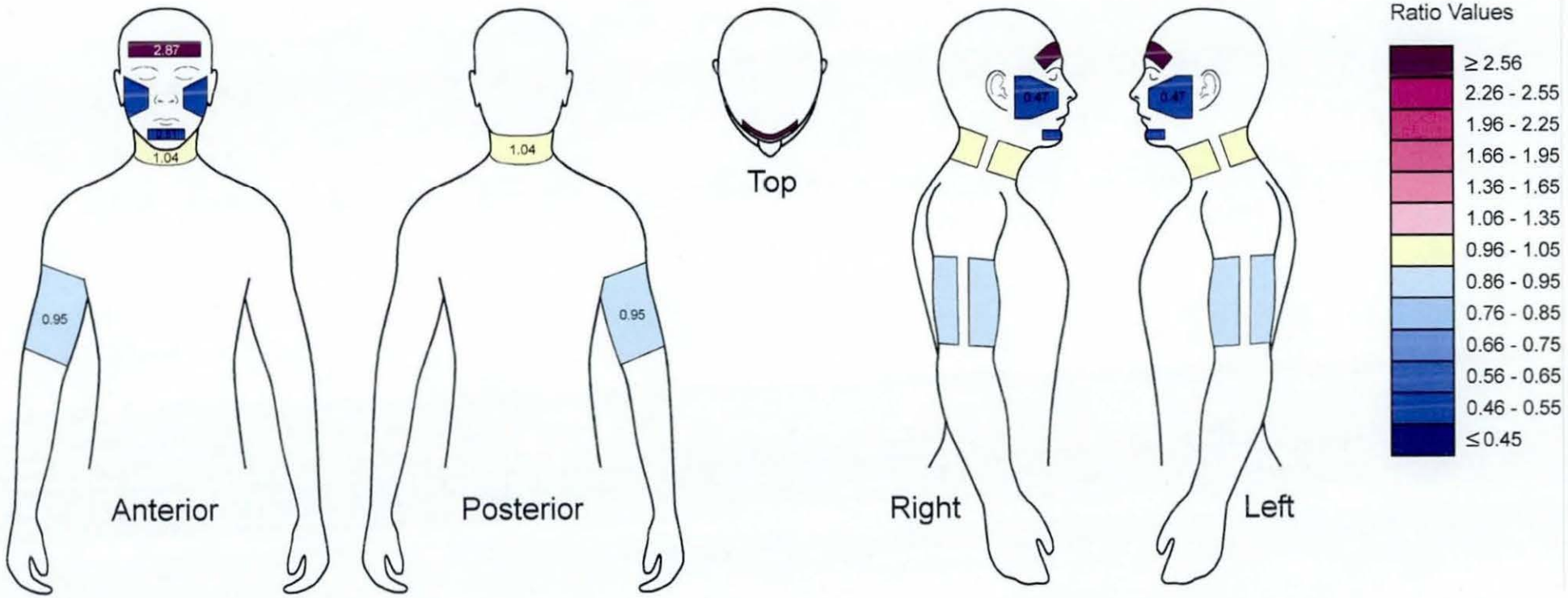


Figure 4.15. Normalised median sweat rate data for the face and neck at I2 (n = 9). A value of 1 indicates a sweat rate equal to the area weighted median sweat rate of all regions measured. Values above or below 1 indicate sweat rates higher or lower than the area weighted median sweat rate of all regions measured respectively.

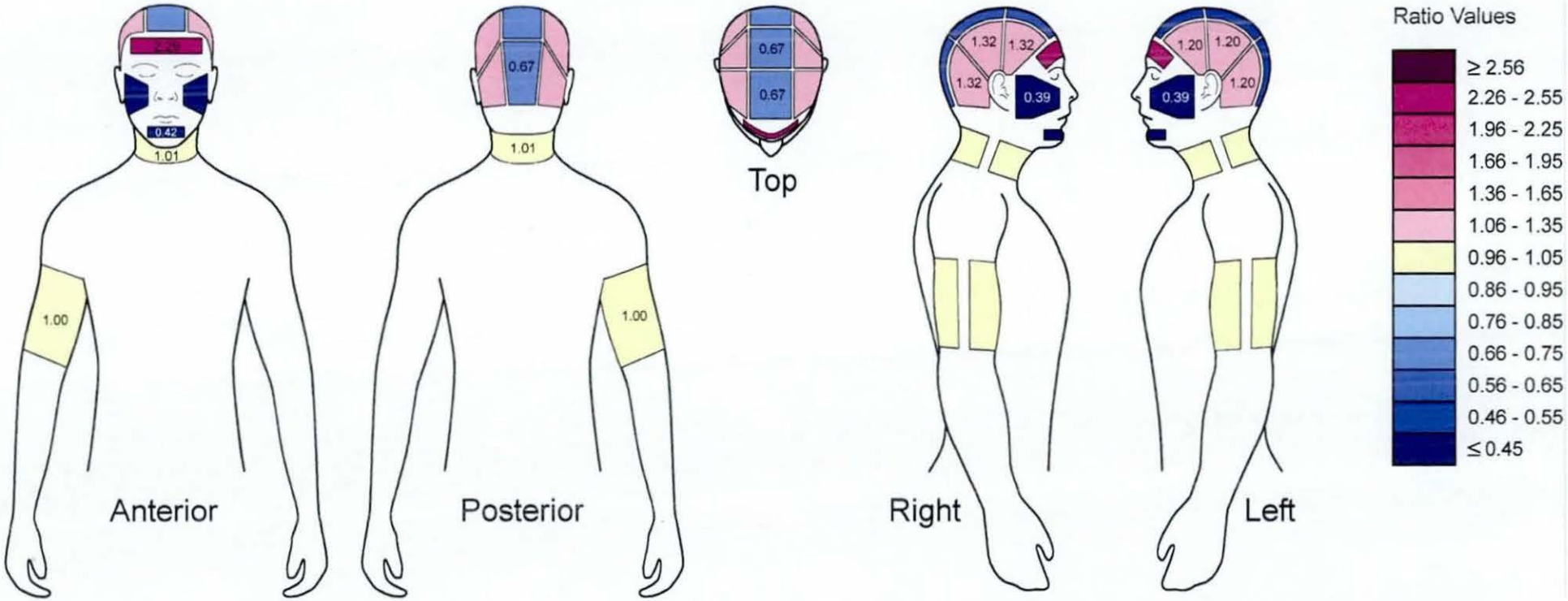


Figure 4.16. Normalised median sweat rate data for the head, face, and neck at I1 (n = 4). A value of 1 indicates a sweat rate equal to the area weighted median sweat rate of all regions measured. Values above or below 1 indicate sweat rates higher or lower than the area weighted median sweat rate of all regions measured respectively.

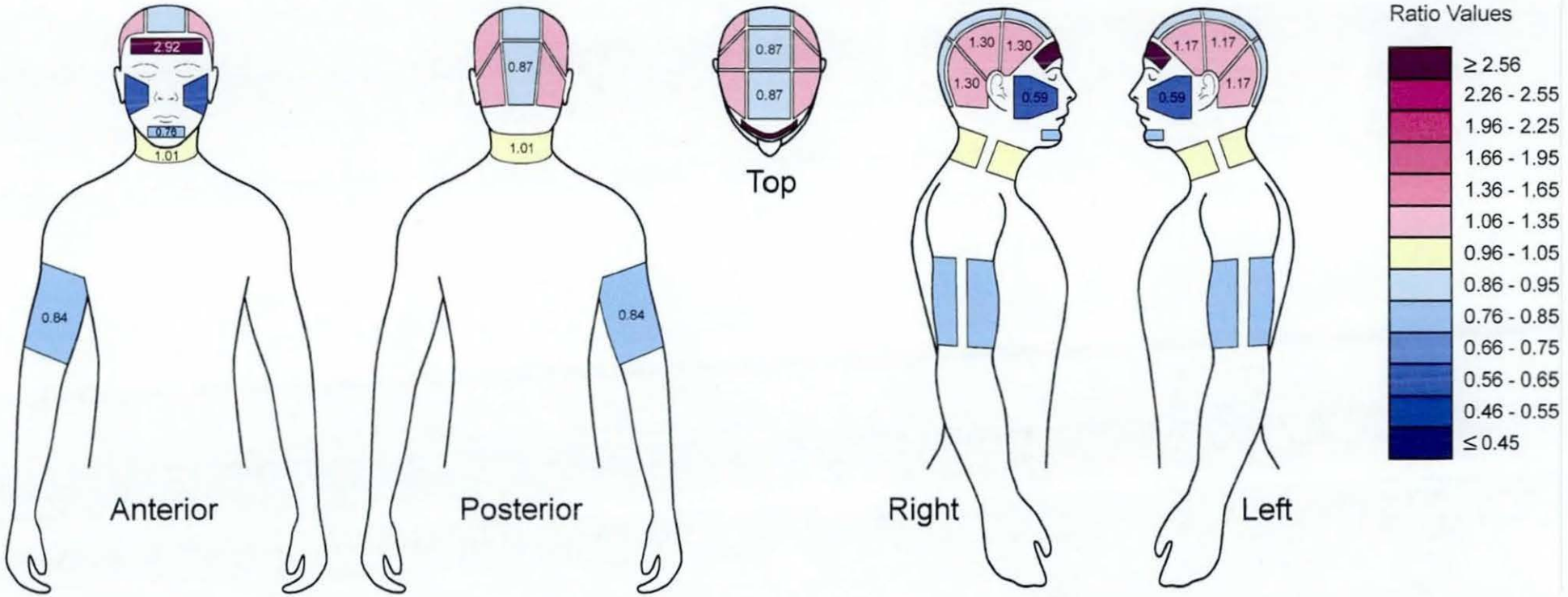


Figure 4.17. Normalised median sweat rate data for the head, face, and neck at I2 (n = 4). A value of 1 indicates a sweat rate equal to the area weighted median sweat rate of all regions measured. Values above or below 1 indicate sweat rates higher or lower than the area weighted median sweat rate of all regions measured respectively.

Table 4.13. Descriptive statistics for all regions sampled on the head, face, and neck at I1 and I2 in male athletes A comparison of sweat rates within each region between exercise intensities for both absolute and normalised data, corrected and uncorrected for multiple comparisons A decrease in median sweat rate between intensities is indicated by grey shading ([illegible])

	Absolute sweat data ($g.m^{-2}.h^{-1}$)										Significance level of intensity comparison	
	I1					I2						
	min	max	median	mean	SD	min	max	median	mean	SD	Absolute data	Normalised ratio data
all participants												
forehead	140	1403	520	667	528	688	2432	1275	1534	671	***###	-
chin	0	166	97	94	57	155	452	225	262	111	**##	-
cheeks	24	328	63	104	96	153	913	208	297	237	**#	*
neck	14	304	215	182	102	68	765	463	443	205	**##	-
arms	72	315	224	209	92	144	575	421	406	140	***###	*
head participants only												
forehead	140	1285	412	562	506	1270	2432	1274	1562	580	**#	-
chin	0	136	75	72	71	215	452	333	333	130	**#	**$
cheeks	24	328	70	123	142	185	913	257	403	344	-	*
neck	67	304	181	183	120	262	765	441	477	212	-	-
arms	72	308	179	184	99	257	481	367	368	94	*	-
medial head	19	460	120	180	201	176	622	379	389	183	-	-
r lat head	27	649	238	288	280	304	966	565	600	306	**#	-
l lat head	34	349	215	203	164	297	832	511	538	253	**##	**$

For conversion to other units divide by 600 to get mg cm^{-2} min^{-1}, or by 10,000 to get ml cm^{-2} h^{-1}
No correction *P ≤ 0 05, **P ≤ 0 01, ***P ≤ 0 001,
Bonferroni correction # P ≤ 0 05, ## P ≤ 0 05, ### P ≤ 0 001, $ 0 1 > P ≥ 0 05

4.3.6 Regional Skin Temperature

A one-way repeated measures ANOVA and post hoc pairwise comparisons were performed on all regional skin temperature data for all separate time points. Based upon significant differences between regions and the biological relevance of those differences, the data was grouped appropriately for further analysis

4.3.6.1 Body Mapping

Regional T_{sk} data were analysed for corresponding right-left differences Significance was present in only 6 regions (pre I1 pads: posterior lower leg $p < 0.05$, posterior upper arm $p < 0.05$; post I1 pads: posterior upper leg $p < 0.05$, posterior lower leg $p < 0.05$; pre I2 pads posterior upper arm $p < 0.05$; post I2 pads posterior upper $p < 0.05$). These differences were not consistently higher over one side of the body or across time points No significant differences were present following Bonferroni correction Data were therefore grouped for corresponding right-left regions for further analysis

Grouped T_{sk} data at all measurement periods are presented in Table 4 14. A series of paired t-tests were performed on all regions to analyse differences between measurement periods. Data are presented both with and without Bonferroni correction. With exception to regions on the legs, arms and hands, T_{sk} increased from baseline (BL) to pre I1 pad application although not significantly. Only the feet and ankles showed a significant increase, reflecting their low baseline temperatures. Of particular interest was the change in T_{sk} between pre and post pad application at both exercise intensities. The torso was most affected by pad application with T_{sk} increasing significantly in all regions When corrected for multiple comparisons only the posterior torso and sides remained significant. Notably, only 6 torso regions showed a significant decrease during exercise intensity 2, and only 2 regions following Bonferroni correction. Over the rest of the body 5 regions showed a significant increase in T_{sk} during I1 pad application During I2 pad application T_{sk} increased significantly in fewer regions, including only 1 region on the torso.

Table 4.14. Regional skin temperature of male body mapping participants at 5 measurement periods baseline (BL), pre I1 pad application (Pre I1), post I1 pad application (Post I1), pre I2 pad application (Pre I2), and post I2 pad application (Post I2) Significant changes within regions from the previous measurement period are indicated by the symbols listed below the table A significant decrease is indicated by grey shading ([illegible])

		Skin Temperature (°C)				
Region		**BL**	**Pre I1**	**Post I1**	**Pre I2**	**Post I2**
UB	anterior medial upper	30 8	31 7	32 64*	32 5	33 9
	anterior lateral upper	30 8	31 1	32 01*	31.4*	33 2
	anterior medial lower	30 0	30 5	31 74*	30 1***##	32 5*
	anterior lateral lower	30 0	31 6	32 27*	31 3**#	33 0
	posterior medial upper	31 0	32 3	33 44**#	33 3	34 8
	posterior lateral upper	31 1	31 4	33 02**#	32 3*	34 3*
	posterior medial lower	29 4	32 4	33 27**$	33 2	34 5
	posterior lateral lower	29 4	31 4	32 63**#	32 0*	33 8
	sides	30 0	31 3	32 34**#	31 4*	33 1***###
Legs	anterior upper	31 1	31 4	32 2	32 4	32 8
	posterior upper	31 7	31 6	32 3**#	33 1	32 9
	lateral upper	31 0	31 3	32 1*	32 5	33 3
	anterior lower	31 5	31 2	31 5	32 2	31 9
	posterior lower	31 7	31 3	31 7	32 9	32 4
AHF	anterior upper	32 5	31 4	32 7**#	31.3**#	32 3**#
	posterior upper	31 8	31 6	32 7*	32 0	32 8**$
	anterior lower	31 5	31 6	32 9**#	32 1*	32 9*
	posterior lower	31 7	31 7	32 8*	32 4	33 0*
	palms	31 5	32 3	33 5	33 2	33 8
	hands	30 4	30 3	31 9	31 4	32 2
	heels	25 8	32 7**#	32 7	33 0	32 7
	soles	27 5	33 5***##	33 4	33 9	33 7
	dorsal foot	28 9	33 6**#	33 5	33 8	33 5
	ankles (anterior)	29 4	32 2*	32 5	32 2	32 2

No correction *P < 0 05, **P < 0 01, ***P < 0 001,
Bonferroni correction # P < 0 05, ## P < 0 05, ### P < 0 001, $ 0 1 > P ≥ 0 05

Regional T_{sk} responded similarly during exercise and pad application within body segments Data were grouped further into body segments to provide an overview of T_{sk} responses during body sweat mapping Figure 4.18 clearly demonstrates the low baseline feet and ankle T_{sk} and the fluctuations with pad application observed in most regions. The mean increase in T_{sk} over all regions during pad application was 0.9°C during I1 and 0 8°C during I2. The largest decrease was observed at the posterior lower leg at I2, with a -0 5°C change in T_{sk}. The largest increase was observed at the anterior medial lower torso with a rise of 2.4°C during I2 pad application.

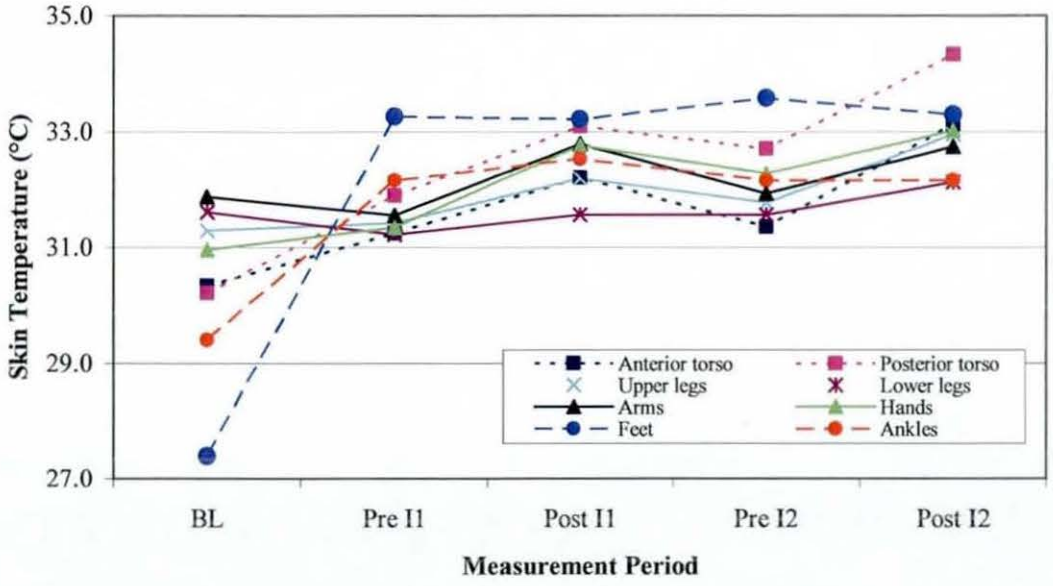


Figure 4.18. Regional skin temperature of male body mapping participants at 5 measurement periods: baseline (BL), pre I1 pad application (Pre I1), post I1 pad application (Post I1), pre I2 pad application (Pre I2), and post I2 pad application (Post I2).

A Pearson's r correlation was performed between regional T_{sk} and regional SR for each participant. Within participant analysis was performed due to between participant factors confounding regional skin temperature and sweat rate. In particular, participants worked at differing absolute work rates producing varied absolute sweat rates. Since significant differences were present in T_{sk} between pre and post pad application, SR was compared with both T_{sk} measurements separately. No strong correlation was observed at I1 and only participant m5 (legs) showed a significant, strong negative correlation at I2 (pre I2 $r = -0.98$, $p < 0.01$; post I2 $r = -0.90$, $p < 0.05$).

4.3.6.2 Head, Face and Neck

Similarly to the body mapping data, regional T_{sk} of the head, face and neck were analysed for corresponding right-left differences. No significant differences were present allowing grouping of the right and left regions for analysis.

Grouped T_{sk} values and significant differences between measurement periods are presented in Table 4.15. T_{sk} decreased significantly from BL to pre I1 pad application in all regions with exception to the cheeks. Similarly to the male body mapping T_{sk}

data, a greater number of regions showed a significant increase during I1 pad application compared to I2. All regions increased significantly from pre I1 to post I1 whilst only 4 increased significantly from pre I2 to post I2. After Bonferroni correction this decreased to 2 regions following I1 pad application and only 1 after I2 Notably, the face and neck appeared to be affected by pad application compared to the head, with regions on the face and neck increasing significantly following I1 and I2 pad application T_{sk} showed no significant on the posterior head following I1 pad application and no increase at any region at I2

Table 4.15. Regional skin temperature of male head, face and neck participants at 5 measurement periods baseline (BL), pre I1 pad application (Pre I1), post I1 pad application (Post I1), pre I2 pad application (Pre I2), and post I2 pad application (Post I2) Significant changes within regions from the previous measurement period are indicated by the symbols listed below the table A significant decrease is indicated by grey shading (▒▒)

	Time point				
Region	**BL**	**Pre I1**	**Post I1**	**Pre I2**	**Post I2**
forehead	33 8	31 8**#	33 4**#	32 5*	34 2**#
chin	33 2	32 1*	33 2**	32 8	33 8**
cheeks	32 8	31 9	33 6**	33 0	34 5**
neck	33 7	30 9***##	32 7**	31 0**	33 4***##
posterior medial head	34 0	31 7*	33 2	31 9	33 7
top (superior) medial head	34 5	32 0*	33 9*	32 3	34 1
side head	34 6	32 4*	33 8*	32 8	34 1

No correction *P < 0 05, **P < 0 01, ***P < 0 001,
Bonferroni correction # P < 0 05, ## P < 0 05, ### P < 0 001, $ 0 1 > P ≥ 0 05

Grouped regional T_{sk} is presented graphically in Figure 4.19. The significant decrease following I1 and the changes in T_{sk} with pad application are clearly evident. The mean increase in T_{sk} of all regions was 1 7°C during I1 and I2 pad application The smallest increase was observed at the chin with a rise of 1.1°C and 1 0°C at I1 and I2 respectively The largest increase in T_{sk} was observed at the neck, increasing by 2 4°C during I2 pad application.

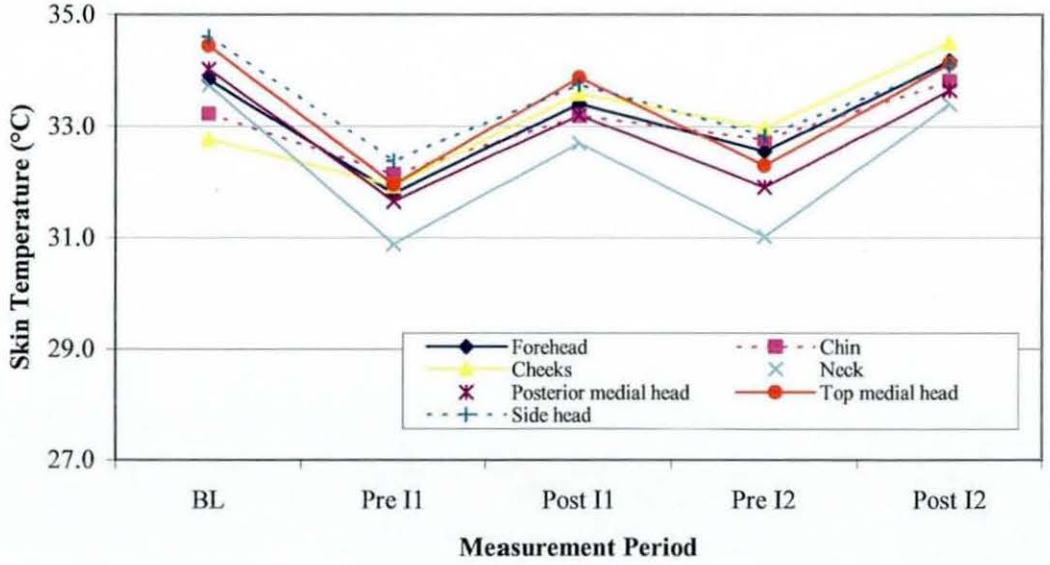


Figure 4.19. Regional skin temperature of male head, face and neck participants at 5 measurement periods: baseline (BL), pre I1 pad application (Pre I1), post I1 pad application (Post I1), pre I2 pad application (Pre I2), and post I2 pad application (Post I2).

As with the body mapping data, within subject correlational analysis was performed between regional T_{sk} and regional SR. A small number of strong correlations were observed, with a mixture of positive and negative r values (m14, post I1 r = -0.91, p = 0.09; m15, pre I1 r = -0.77, $p < 0.05$, post I1 r = -0.73, $p < 0.05$; m9, post I2 r = -0.77, p=0.232; m13, post I2 r = 0.86, p = 0.139). No participant consistently demonstrated a strong correlation between regional T_{sk} and regional SR across measurements periods.

4.4 Discussion

4.4.1 Core Temperature

A mean increase in T_{core} from BL to I1 of 0.76 ± 0.18°C ($p < 0.001$) and 0.55 ± 0.26°C ($p < 0.01$) was observed in body mapping and head and face participants respectively. The greater rise in T_{core} observed for body mapping participants reflects the lower BL temperature. A significant increase in T_{core} of 0.37 ± 0.23°C ($p < 0.001$) and 0.36 ± 0.19°C ($p < 0.05$) between exercise intensities was observed in body mapping and head and face participants respectively. The significant increase in T_{core} observed from I1 to I2 in all participants is typical of the body's thermoregulatory response to exercise,

and/or high ambient temperatures. Regardless of the negative feedback loop by which the thermoregulatory system operates, a gradual rise in T_{core} is necessary to elicit a proportional increase in SR, and therefore increased evaporation (Werner, 1993) T_{core} stabilises at a higher level during exercise, with the increase in T_{core} being proportional to the intensity of exercise during steady state, and independent of T_a (within the prescriptive zone, Nielsen, 1938) This relationship of proportionality results from a greater metabolic heat production in muscles with increased exercise intensity, causing an increase in body heat storage The degree of heat storage is determined by the accumulative difference in metabolic heat production and whole body net heat loss (evaporative and dry heat losses). Heat storage and hence T_{core} will increase following the initiation of exercise, and will continue to increase unless a constant heat production (exercise intensity) is performed which may be balanced by net heat losses, resulting in a stable but elevated T_{core} (Kenny *et al*, 2008). Since participants were all exercising at a similar specified relative workload, no significant differences in T_{core} at I1 or I2 between the body mapping and head and face groups were observed. It must however be considered that since there was a significant difference in $VO_{2\ max}$ between groups, although working at a similar relative workload the absolute workload, and thus heat generation, would be substantially higher in those with a higher $VO_{2\ max}$ (discussed in 4.4.2. Gross Sweat Loss) Mean T_{core} over I1 and I2 was plotted against mean metabolic rate (average of all experiments) over both exercise intensities (Figure 4.20)

Participant m8 was identified as an outlier (studentised residual >2, leverage value >2*average leverage value) but analysis is reported both with and without this data point. No correlation was present between T_{core} and metabolic rate for both groups under the given conditions (body mapping, Incl m8 r = -0.19, excl m8 r = 0 46, head and face, r = 0 26) When the groups were combined a moderate, negative, significant correlation was present between T_{core} and metabolic rate (combined groups, incl m8 r = 0 25, excl m8 r = - 0.51, $p < 0\ 05$). Participant m10 showed a high studentised residual value when the groups were combined but did not exert undue influence (small leverage value and Cook's distance) The slight negative tendency in the data is surprising since it is well established in literature that T_{core} increases with an increase in work rate

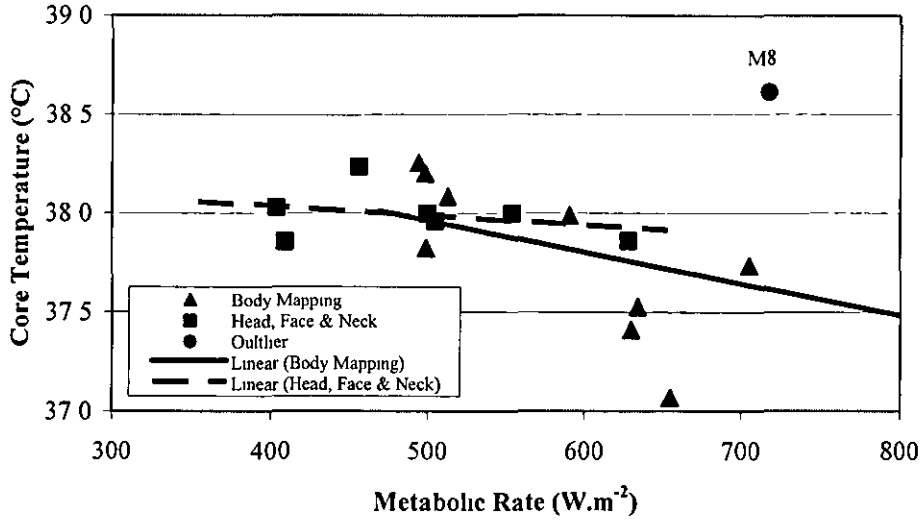


Figure 4.20. Mean core temperature and mean metabolic rate for body mapping and head, face and neck participants

Given the similarity in T_{core} yet significant difference in metabolic rate ($p < 0.05$), participants with a higher $VO_{2\ max}$ were working at a higher absolute work rate yet experiencing no greater increase in T_{core}. These findings support a rise in T_{core} being determined by relative rather than absolute work rate (Neilsen,1938; Saltin and Hermansen, 1966, Nielsen and Davies, 1976). This may be explained by the close relationship between cardiovascular capacity and cardiac output A rise in T_{core} may be determined by the availability of circulatory capacity for conductive heat transfer from the core to skin (Nielsen and Davies, 1976) Participants with a higher $VO_{2\ max}$ were working at a higher metabolic rate but were better able to dissipate the heat as a result of their superior circulatory capacity, provided they achieve sufficient sweat production.

4.4.2 Gross Sweat loss

Considerable variation was observed both within and between participants for *GSL* in body mapping participants. The mean absolute difference between experiments on the same participant was 77 ± 60 g m^{-2} h^{-1} with a range from 8 to 203 g m^{-2} h^{-1}. Participants performed all of their experiments at the same time of day which negates circadian variation as a factor in intra individual variation however may account for some degree of variation between participants. There is a possibility of differing T_{core} between

experiments however it is unlikely to be considerable enough to cause such large intra individual variation in gross sweat loss T_{core} was measured during one of the three experiments for all participants since the experimental procedure was identical for all sessions. The expense of the core temperature pills made it impractical for three repeated measures for each participant On balance it was decided that one measurement was sufficient considering data would be averaged over all individuals. Participant m10 was requested to take a pill for all experiments to assess variability Results indicated that T_{core} showed little variation across experiments with a mean (± SD) of 36.45 ± 0.2°C, 37.10 ± 0.3°C and 37.57 ± 0 2°C for baseline, I1 and I2 respectively

GSL increased significantly ($p<0$ 001) with exercise intensity in all participants in both body mapping and head, face and neck experiments. A mean increase of 291 ± 95 $g.m^{-2}.h^{-1}$ and 295 ± 98 g m^{-2} h^{-1} between I1 and I2 was observed for the body mapping and head, face and neck respectively. This thermoregulatory response results from an increase in metabolic heat production with increased exercise intensity, eliciting a proportional increase in *SR* (discussed in section 4.4.1) When plotted against $VO_{2\ max}$, *GSL* was higher in those with a higher $VO_{2\ max}$ (body mapping, r=0 88, $p<0$ 001, head, face and neck, r = 0.77, $p<0$ 05), yet against T_{core} a negative, non significant correlation was observed (body mapping, r = -0 07; head, face & neck, r = -0 02) *GSL* (g $m^{-2}.h^{-1}$) was subsequently plotted against metabolic rate (W m^{-2}) for I1 and I2 separately (mean of all experiments) for the body mapping (Figure 4 21) and for the head, face and neck (Figure 4 22). In both groups, a significant positive correlation was observed for I1 and I2 with exception to I1 for the head, face and neck participants which was close to significance (p = 0.054). A Pearson's r correlation coefficient of 0 87 ($p<0.01$) and 0.72 ($p<0$ 05) were observed for I1 and I2 respectively for body mapping and 0 66 (p = 0 54) and 0.75 ($p<0.05$) for I1 and I2 respectively for the head, face and neck When both groups of data are combined, a significant, positive correlation is observed at both exercise intensities (I1 r = 0 93, $p < 0$ 001; I2 r = 0 90, $p < 0.001$) Since all participants were working at a similar percentage $VO_{2\ max}$ for each intensity, it would appear that the correlation observed between *GSL* and predicted $VO_{2\ max}$ in fact results from a difference in absolute work rate (Nielsen, 1969, Kenny and Jay, 2007). No significant difference in the gradient of the regression lines was present between intensities in the

male athletes or the head, face and neck groups, indicating no change in the sensitivity of sweating (increase per unit increase in work rate) between exercise intensities when analysed as a group However, although the sensitivity as a group within each workload is the same a direct comparison shows that sweating is greater for I2 than I1 for the same absolute workload (difference in constant)

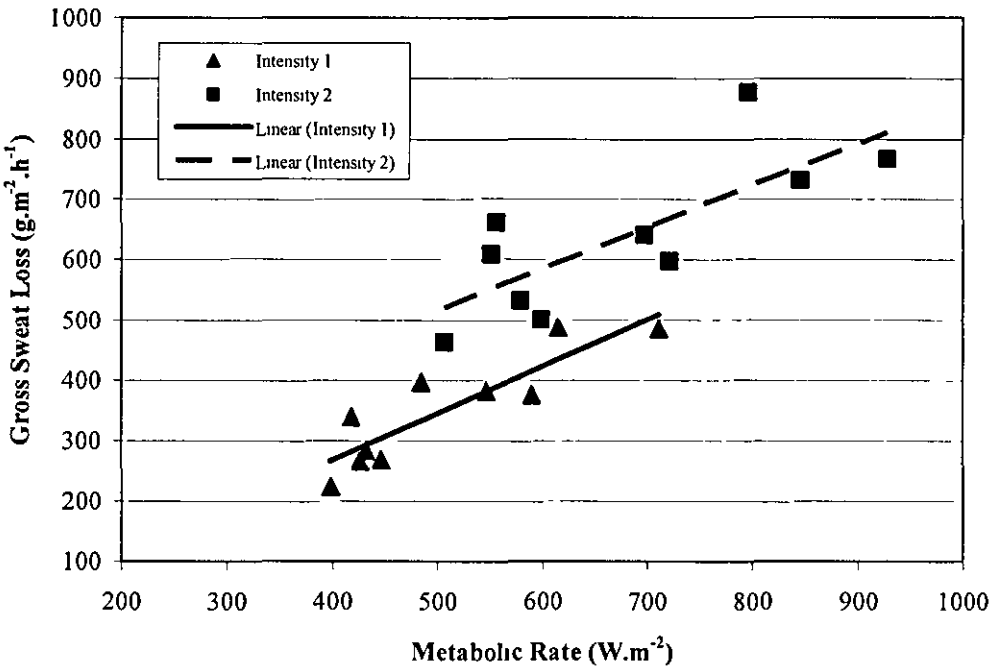


Figure 4.21. Gross sweat loss and metabolic rate at I1 and I2 for all body mapping participants

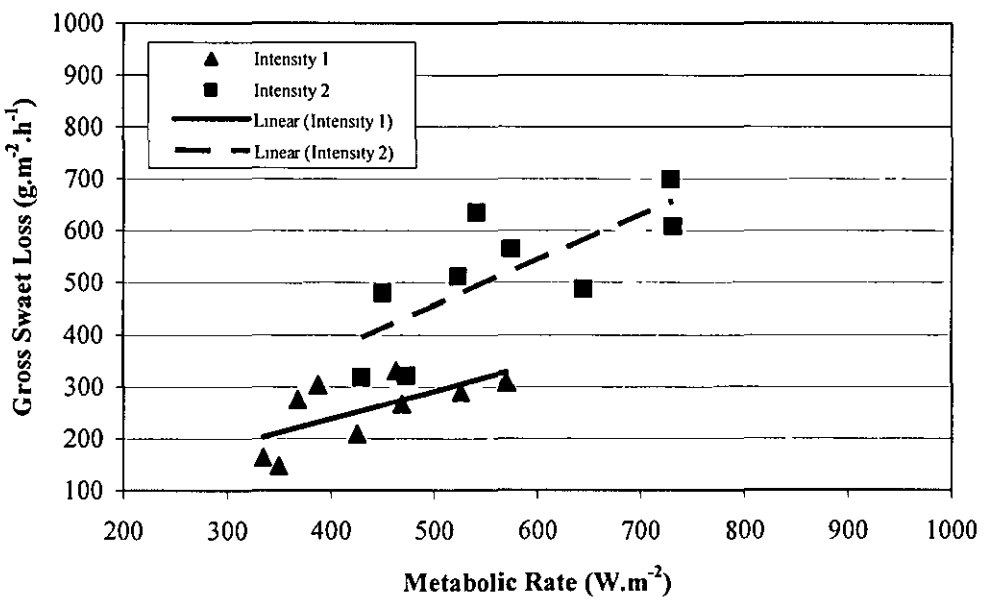


Figure 4.22. Gross sweat loss and metabolic rate at I1 and I2 for all head, face and neck participants

Some variation in *GSL* between participants or groups may result due to differences in mechanical power, mechanical efficiency, and body mass when a relative workload is imposed, resulting in a differences in heat balance and therefore *SR*. However, if all participants were to work at the same absolute metabolic rate then one might expect that those with the higher predicted $VO_{2\ max}$ may display a higher *GSL* than participants with a lower $\dot{V}O_{2\ max}$, as it is widely accepted that athletes are to some degree 'heat acclimatised' as a result of regular bouts of high intensity exercise producing high T_{core} values (Robinson *et al*, 1943; Greenleaf, 1964; Piwonka *et al*, 1965; Fox, 1968, Cotter and Taylor, 2006) One important indication of heat acclimation/acclimatisation is an increase in *SR* (Winslow *et al.*, 1937, Gagge, 1937, Candas *et al*, 1979a, 1979b; Candas, 1986). It would therefore seem logical to suggest that participants with a higher predicted $VO_{2\ max}$ would produce a higher *GSL* when working at the same absolute ($\dot{V}O_2$) workload as those with a lower predicted $\dot{V}O_{2\ max}$ due to this 'training effect'

GSL was calculated in two ways during the current study, firstly, from weight change, and secondly as a *SA* weighted *SR* from all regional sweat rates measured One might expect some variation between the two values since the latter measured regional *SR* over a 5 minute steady state exercise period whilst the *GSL* calculated from weight change includes the whole exercise period Visible sweating was not present during the initial few minutes of exercise which was used to achieve a steady state This suggests an underestimation of *GSL* (Δ weight) compared to *SA* weighted *SR*. This was however not the case, with *GSL* significantly higher for the body mapping experiments at both exercise intensities (I1 $p < 0.01$, I2 $p < 0\ 001$) The two values varied in the quantity of the body which was measured. *GSL* calculated from weight change encompassed the whole body as opposed to selected regions of the body used in *SA* weighted calculations of sweat loss. Regions including the head and axilla are recognised to possess high sweat rates but were not included in the whole body sweat mapping. *SA* weighted *SR* calculations included only the regions measured by pads and so the absence of high sweat regions would lower the calculated *SR* When calculated for separate body mapping experiments, the difference between *GSL* and *SA* weighted *SR* decreased for the upper body and was greatest for the extremities This difference followed the order of high to low sweat rates over the body, consistent with

the analysis above The source of the variation between the calculations resulting from the regions being *SA* weighted is supported by the non significance observed between *GSL* and *SA* weighted *SR* for the head, face and neck at I1 and I2

Considering the sweat collection technique used in the current research necessitates application of absorbent material directly to the skin, two factors may be highlighted with regard to the observed difference in *GSL* and *SA* weighted *SR* , 1) pressure effects, and 2) hidromeiosis. By its very nature, the absorbent method will to some extent disrupt the microclimate of the skin and the evaporative process. This was minimised through short measurement periods and monitored through *IR* analysis of skin temperature., but the question of the extend of this effect must be considered

Application of pressure to the skin has, in a limited number of studies, demonstrated a suppressive effect on regional *SR* whilst augmenting *SR* in contralateral regions This hemihidrotic effect was first recognised by Kuno in 1934 (Kuno, 1956) and later confirmed by Takagi and Sakurai (1950, cited in Kuno 1956) This response could be elicited by pressing the axillary and pectoral regions with objects as small as a pencil This hemihidrotic reflex was not observed by Watkins (1956) in West Africas. Change in *SR* from one side of the body to the other was observed equally both with and without the application of pressure A suppressive effect upon regional *SR* as a result of pad application may explain a lower *SA* weighted *SR* than *GSL* If *SR* were augmented in regions where pads were not applied, *GSL* would be greater whilst *SA* weighted *SR* would underestimate *GSL*. This is unlikely since the hemihidrotic reflex had been observed in instances of localised pressure applied to the axilla and has a latent period of several minutes Ferres (1960) further suggests that pressure less than 5kg fails to elicit a hemihidrotic effect. The current method applies a light uniform pressure over large regions and covers both sides of the body. A hemihidrotic effect is therefore unlikely to influence regional *SR* in the current study.

A second factor of note is hidromeiosis Under conditions of high skin wettedness, a decline in sweat rate may be observed due to epidermal swelling Since evaporation is restricted during absorbent pad application it may be possible that an increase in skin wettedness results in hidromeiosis. If so, a local suppression of sweat rate would be

observed at the regions of sweat measurement, explaining the discrepancy between *GSL* and *SA* weighted *SR*. This explanation seems unlikely since hidromeiosis requires high levels of skin wettedness and develops over a much greater time period than used for pad application (Kerslake, 1972; Candas *et al*, 1980; Candas, 1986). The material used for sweat measurement possessed a highly absorbent property, removing the sweat away from the surface of the skin Only under conditions of prolonged application would hidromeiosis pose a problem

4.4.3 Regional Sweat Rate

Whole body sweat mapping on male athletes has clearly demonstrated regional variation in sweat rates and that the variation is considerable both within and between individuals Although the quantity of sweat produced differed amongst participants, the general patterns remained consistent Regional variation in eccrine sweating is well documented (Weiner, 1945, Kuno, 1956; Hertzman, 1957; Cotter *et al*, 1995) however only recently has research indicated intra regional variation (Taylor *et al*, 2006, Fogarty *et al*., 2007; Smith *et al*., 2007, Havenith *et al*., 2008, Machado-Moreira *et al*., 2008a, 2008b, 2008c). Since a total of 2-5 million eccrine sweat glands are densely populated over the whole body surface (Kuno, 1956), variation in density must be considered in relation to regional *SR*. In addition, the secretory activity of sweat glands varies from one gland to another, with some glands being inactive (Sato, 1934, cited in Kuno, 1956, pp 57) Regional differences in sweat rate may therefore be largely considered through variation in two factors; 1) eccrine sweat gland density and 2) output per gland.

Despite large individual variation in *SR*, a clear pattern of distribution was observed, with significant differences between regions The highest values were observed on the posterior torso, in particular on the central upper, central mid, and lower back. The anterior torso and shoulders followed as areas of next highest sweat production, yet values were over half that of the posterior torso. The lowest *SR* s were observed on the extremities, particularly the feet, palms, and fingers The regional variation observed in the present study is largely supported by the classic, mainly qualitative work of Kuno (1956, pp. 193-195) and more recently by studies looking in detail at single regions, Taylor *et al*., (2006, feet), Fogarty *et al* (2007, feet), Smith *et al* (2007, hands and arms), Havenith *et al*. (2008, torso), and Machado-Moirera et al. (2008a, torso, 2008b,

head, 2008c, hands) In agreement with the current findings, they identified areas of high sweat production to be the forehead, neck, large areas of the anterior and posterior trunk, and the lumbar region. Regions of low sweat production were observed to be the sides of the chest, all extremities, and the internal femoral region Following colorimetric investigation over the whole body in 105 Japanese males, Kuno stated that without exception, all men sweated most on the back (Kuno, 1956, pp 198) This observation, although qualitative, is strongly supported by Machado-Moreira *et al.* (2008a), Havenith *et al.* (2008), and the findings from the current study Notably, Japanese participants were used in much of Kuno's work, yet many similarities in high-low sweat distribution seem apparent in comparison to the current data which used Caucasians. Weiner (1945) further confirmed these findings following localised capsule measurements in 30 regions of the body, and assigned values of 50, 25, and 25 percent to the trunk, legs, and head and upper extremities respectively for contributions to total sweat production

Regional sweat distribution does not necessarily correspond to eccrine sweat gland density (Ogata, 1935). Cadaver data by Szabó (1962) found the highest densities (± SE glands cm^{-2}) on the soles (620 ± 120), forehead (360 ± 50), and cheeks (320 ± 60) Lower densities were present on the dorsal foot, forearm, abdomen and chest, with values ranging from 250 ± 5 to 175 ± 35 respectively The lowest values were on the back, buttocks, lower legs, upper arms, and thighs with values from 160 ± 30 to 120 ± 10 respectively The small cadaver samples traditionally reported by Szabó must be noted, whilst in agreement with some studies (Krause , 1844, cited in Kuno, 1956, p64-66), debate does surrounds the exact numbers of regional eccrine sweat glands A comprehensive review of torso sweat gland densities from a large body of literature was recently produced by Machado-Moreira et al. (2008a), providing more reliable values Mean glandular density was highest on the abdomen (115 glands.cm^{-2}), upper back (104 glands.cm^{-2}), chest (102 glands cm^{-2}) and the lower back (101 glands cm^{-2}) Lower values were observed on the chest (sternal, mammary) and abdomen with values of 90, 21, and 81 glands cm^{-2} respectively. Given the relatively uniform glandular density on the torso, the large variation in regional *SR* cannot be explained by the total number of glands. It would therefore seem logical to consider the number of active sweat glands, output per gland, and sudomotor sensitivity. Machado-Moreira *et al* (2008a) calculated intra segmental sudomotor sensitivity, with results relating closely to the regional

variation in *SR* observed in the current study Differences in sudomotor sensitivity were not significant across the torso, with considerable variation between participants being reported. This alone fails to explain regional variation in sweat rate, however may be considered in conjunction with sweat gland density.

When compared with sweat droplet analysis by Ogata (1935, cited in Kuno, 1956, Pp 72), regions showing the greatest sweat gland activity appear to parallel high sweat regions. Ogata observed central zones of the anterior (ventral) and posterior (dorsal) surfaces of the torso to be most active, followed by other regions of the trunk, neck, and face. Less activity was observed on the extremities, particulalry on the palms and soles This regional relationship appears to correlate with the average size of sweat glands Kodachi (1942, cited in Kuno, 1956, Pp. 74) found a strong correlation between glomerular size and regional sweat distribution. These results support the male body mapping data, suggesting regional sweat variation to result from differences in eccrine gland and glomerular size, contributing to variation in the secretory activity of individual glands. Those regions with larger eccrine glands, rather than higher gland density, may therefore produce higher sweat rates

The observed decrease from medial to lateral regions across the torso has been reported by some authors (Ogata, 1935; Kuno, 1956; Hertzman, 1957, Havenith *et al.*, 2008, Machado-Moreira *et al*, 2008a) Ventilated capsule work on males by Machado Moirera *et al*, (2008a) produced a similar pattern, with medial *SRs* being approximately double those of lateral regions In the present study, lateral *SR* s were approximately two thirds of the medial *SR* on the anterior torso at I1 and I2, and approximately one third on the posterior torso at both exercise intensities Machado Moirera *et al* (2008a) observed greater *SR* s were observed on the posterior compared to anterior torso, similarly to findings in the current study, however they observed significant intra-segmental differences to be accentuated with increases in exercise intensity. The absolute values obtained by Machado-Moreira *et al*, (2008a) appear comparable with I2 of the current sweat mapping data however the shoulders, anterior torso (chest and abdomen), and lateral regions are higher than the present results Discrepancies may result from data analysis since they presented an average over all progressive exercise intensities as opposed to data at each stage, however the average

would be lower than if taken at a latter stage of the testing. Differences may have arisen for methodological reasons Ventilated capsules require completely dry skin, which although avoids hidromeiosis, may artificially increase local *SR* (Candas *et al.*, 1980, 1983, Stolwijk and Nadel, 1973). Conversely, the increased evaporation may lower T_{sk} and hence *SR* (Van Beaumont and Bullard, 1965; Ogawa and Asayama, 1986) The absorbent technique used in the present study may reduce sweat rate as a result of the increasing wettedness of the patches (Inoue *et al.*, 1999), yet increase T_{sk} and therefore *SR* due to reduced evaporation (Havenith, 2001) These effects were minimised through short application periods and by using pads with a much higher absorption capacity than required.

Hertzman (1957) identified a lateral decrease in *SR* however observed an approach to uniformity in regional *SR* with increasing heat stress, contrary to the present body mapping data. Results from Cotter *et al* , (1995) do not concur with the current findings, suggesting no medial to lateral decrease on the torso and showing greater absolute regional *SRs* on the hands and arms (1230 and 1290 $g.m^{-2}.h^{-1}$, forearm) than indicated in the present data. Their participants were however exposed to higher ambient temperatures yet a lower exercise intensity Kuno (1956, pp 200) reported scant sweating on the side of the chest, inside (anterior) of the arms, and flexural surface of joints. Regions of the skin covering joints were not measured in the body mapping since the absorbent material would not remain sufficiently in place and caused restriction to movement. Lower sweat rates were however observed on the side of the chest in comparison to other areas of the torso and tended to be higher on the distal regions of the arm The evaporative heat transfer coefficient of the arms is higher during motion, causing the low *SRs* to appear counterintuitive in the context of optimising heat loss

Few studies have been conducted on *SR* s of the head and face, making the comparison of data limited. A recent and very detailed study by Machado-Moreira *et al.* (2008b) analysed 10 sites (6 lateral head, 3 medial head, 1 forehead) using ventilated capsules (3.16 cm^2 area per capsule) Similarly to Machado-Moreira *et al* (2008b) the current data observed the highest sweat rates on the forehead and lateral head with values as high as 520 and 1275 $g\ m^{-2}\ h^{-1}$ at the forehead for I1 and I2 respectively. The forehead was significantly higher than all other sites (grouped data) at intensity 2, whilst no

significant differences were present at intensity 1. Sweat glands density (±SE) on the forehead has been observed to be the highest on the body, with values of 360 ± 50 glands.cm^{-2} (Kuno, 1956; Szabo, 1962). Yet the responsiveness of these glands has been shown to be low in comparison to other sites (Patterson *et al*, 2004). This may explain the non significance observed between the forehead and all other regions during I1 yet a significantly higher sweat rate than almost all other sites during I2. Ungrouped data showed a number of significant differences at I2, particularly between sites on the face and the head, highlighting areas with the lowest and highest sweat rates respectively

Similarly to the rest of the body, *SR* s of the head and face do not appear to correspond to regions of high glandular density. The lowest *SR* s at both exercise intensities were observed at the cheeks (I1 63 g m^{-2} h^{-1}; I2 208 g m^{-2} h^{-1}) and chin (I1 97 g m^{-2} h^{-1}; I2 225 g.m^{-2}.h^{-1}) The cheeks have a relatively high sweat gland density of 320 ± 60 glands cm^{-2}, suggesting a low output per gland or a high number of inactive glands Sweat rates on the head showed little variation with exercise intensity The fairly uniform sweat rates over the head, face and neck in the present study are not in agreement with the greater variation observed by Machado-Moreira and colleagues (2008b). In particular, they observed a significant increase from medial to lateral regions on the head Although not significant, the medial head did show lower sweat rates than the lateral regions in the present data with values of 120, 238, and 215 g m^{-2} h^{-1} for the medial, right lateral, and left lateral head respectively at I1 and 379, 565, and 511 g.m^{-2} h^{-1} at I2. Notably, only 4 males were measured in the current study Considering the large individual variation in regional *SR*, a larger sample size may produce significance.

One important point to consider when analysing data of the head is the influence of hair Machado-Moreira et al (2008b) found *SR* s on the forehead to be higher than the head, which appears logical due to lacking in hair and therefore experiencing a high evaporation rate from exposure to front wind. They concluded that glabrous (non-hairy) skin secreted more sweat than non glabrous (hairy skin) Machado-Moreira and colleagues did not measure any other sites on the face except the forehead The current data suggests that the lowest *SR* s are observed on the cheeks and chin, whilst the highest are observed on the forehead and lateral head The conclusion that *SR* on non

glabrous skin are lower than those on glabrous skin appears logical since evaporation is hindered by the presence of hair. This may however not be the case in individuals who are bald. In the current study, participant m12 was essentially bald and showed much greater *SR* s on the head than the other subjects who had hair *SR* s over the medial, right lateral, and left lateral head were 460, 649, and 389 g m^{-2} h^{-1} respectively at I1 and 392, 966, and 662 g $m^{-2}.h^{-1}$ at I2 In contrast, m12 showed much lower *SR* s of 110 and 136 $g.m^{-2}.h^{-1}$ for the cheeks and chin respectively at I1 and 185 and 452 $g.m^{-2}.h^{-1}$ at I2 In the absence of hair, *SR* s over the head may be higher than in individuals with hair The question of possible adaptation of sweat glands to loss of hair is important, particularly with regard to male pattern baldness A correlation between sweating and the presence of hair by was observed by Cabanac and Brinnel (1988), who suggested the development of male pattern baldness in response to facial hair growth as a mechanism for maintaining a constant evaporative rate over the head and face The acute impact of shaving hair, with potential irritation to the skin, on *SR* in the current study is however unknown.

Comparison between the present absolute data and the relevant literature is problematic since differing temperature and exercise protocols have been adopted Discrepancies in data may also arise from methodological issues since some techniques promote complete evaporation at the skin (ventilated capsules) which may artificially elevate *SR* whilst others prevent evaporation, potentially causing increases in T_{sk} and therefore *SR* (absorbents) It is worthy of note that any method employed in sweat measurement will interfere to some degree with the microclimate of the skin and hence the local T_{sk} and *SR* . Absorbents have previously been used in sweat research (Kalkan, 1998, Fogarty *et al.*, 2007, Havenith *et al.*, 2008) however not as extensively as in the current study Large areas of the body were simultaneously measured, however unlike the ventilated capsule method, continuous measurement over time is not possible. Short measurement periods were used to prevent hidromeiosis and excessive increases in T_{sk} . Light uniform pressure was applied to the skin for the application of the absorbent pads, however it is unlikely that this had any effect upon the regional sweat distribution (Ferres, 1960).

4.4.4 Regional Skin Temperature

The regulation of body temperature during exercise is dependent upon both sweating and alterations in skin blood flow. T_{sk}, and ultimately evaporative cooling, are influenced by cutaneous vasomotor adjustments which determine convective of heat from tissues to the skin (Robinson, 1962) As a component in the thermoregulatory control loop, T_{sk} operates via negative feedback. As skin temperature rises upon exposure to high ambient temperature or during exercise, sweating is initiated to reduce body temperature (both core and skin). Fluctuations in T_{sk} arise from resultant fluctuations in regional sweat evaporation, reflecting the balance between sweating and cooling. The dynamic interplay of T_{sk} and SR may explain the weak correlation observed between local T_{sk} and regional SR. Cotter *et al.*, (1995) observed similar findings, with a low correlation between local T_{sk} and SR during transient sweating (r = 0 16), and only 2.5% of steady state sweating being explained by variation in local T_{sk}

The regional T_{sk} data in the current study, although showing significant differences between some regions, does not provide sufficient support as a cause for regional variation in SR. An interdependence of local sweat rate and T_{sk} has long been suggested (Randall, 1947; Kuno, 1956) yet much debate has surrounded the role of skin temperature in thermoregulatory control. Van Beaumont and Bullard (1965) demonstrated both mean and local T_{sk} to be important factors in thermoregulatory control. Nadel *et al*, (1971) further identified local T_{sk} as a modifier of central output, causing a non-linear, exponential rise in local SR with an increase per unit temperature rise. Local T_{sk} may indeed act as a modifier of local SR, however fairly narrow temperature ranges were observed during exercise in the current study (31.0°C-34 5°C), possibly limiting the visibility of such an effect Benzinger *et al*, (1961) suggested that SR is not modified by T_{sk} in the range of 33-39°C, but is related solely to hypothalamic temperature. Notably, only one male participant was used by Benzinger, making the generalisation of the data questionable given the considerable inter-individual variation observed in human thermoregulatory responses. Influences of local T_{sk} on SR have

additionally been found by other authors within such temperature ranges (Van Beaumont and Bullard, 1965, Libert *et al*, 1979, 1983) This suggests that the act of peripheral modification of SR may not be restricted to narrow temperature ranges, although as suggested by Randall (1974), may only occur above a threshold T_{sk}

Since sweat measurement in the current study required the skin to be covered, consideration for its impact upon regional T_{sk} is necessary Despite no strong correlation between regional SR and regional T_{sk}, the highest SR s over the body were observed in the regions most affected by the application of absorbent pads. T_{sk} increased significantly during I1 pad application on the posterior torso ($p < 0\ 01$) and forehead ($p < 0\ 01$), both with and without Bonferroni correction ($p < 0\ 05$). One might argue that the sweat rates in these regions were artificially raised by the increase in T_{sk} Although some degree of increase is unavoidable using the absorbent technique, measurement periods were short to minimise effects upon T_{sk} Notably, T_{sk} did not decrease following I1 pad application in the majority of regions and only 11out of 31 regions (seven body, four head and face) increased significantly during I2 application The latter suggests that pad application has minimal interference with T_{sk} since few significant differences were present at the higher workload when greater heat dissipation was required from the body.

4.5 Conclusions

Sweat mapping of the body, head, face and neck in male athletes was completed during steady state exercise in a moderate environment. The following conclusions were drawn·

- Large intra and inter individual variation was observed in both regional and gross sweat loss.
- Despite large variation in absolute regional sweat rates, consistent patterns were observed between individuals.
- The highest absolute sweat rates were observed on the medial and lower posterior torso and the forehead at both exercise intensities.

- The lowest sweat rates were observed on the fingers and palms for the body, and the cheeks and chin for the head, face and neck sweat mapping.
- Regional sweat rate increased significantly with exercise intensity in most regions, with exception to the feet and ankles
- Little change in distribution was observed with an increase in exercise intensity, with exception to a significant decrease in the relative sweat rate on the feet
- Regional skin temperature increased significantly in some regions following pad application but this was not thought to affect sweat rate Skin temperature increased significantly in most regions during I1 pad application but did not decrease at I2, and few regions increased significantly during I2 pad application.
- No correlation was observed between skin temperature and sweat rate at either exercise intensity.

Chapter 5

Study 3: Body Sweat Mapping in Female Athletes

5 Chapter Summary

This chapter explores the regional variation in *SR* s in female athletes, and additionally provides a comparison with the male sweat mapping data presented in Chapter 4. Participants were required to exercise at two different intensities during each experiment, with the whole body progressively mapped over three experiments. Considerable gross and regional variation in sweat rate was observed both within and between female participants. A significant difference in *GSL* and regional absolute data was observed between males and females. A number of significant differences were present in normalised regional data between sexes, illustrating variation in distribution, however these differences became less pronounced with exercise intensity. Despite some differences in distribution, both sexes showed the highest *SR* s on the central posterior torso and the lowest towards the extremities

5.1 Introduction

Similar to literature regarding sweat rates in males, data on females focuses predominantly on *GSL* Sparse data is available on regional *SR* s, and is limited to a small number of sites over the body covering a minimal *SA* per region A comparison of detailed male and female regional *SR* data is therefore limited

Considerable debate surrounds sex differences in thermoregulatory function. Research typically indicates women to regulate body temperature less effectively than males in dry heat (Shapiro *et al*, 1980), with maintenance of a higher rectal temperature in women compared to males, and a substantially lower *SR* (Fox *et al*, 1969; Bittel and Henane, 1975; Shapiro *et al*., 1980a, 1980b, Frye and Kamon, 1981, Havenith *et al*, 1995; Havenith 2001a; 2001b) A more pronounced delay in sweating onset has additionally been observed in women, attributed in part to lower body water content

(Grucza *et al.*, 1985), and potential effects of menstruation (Bittel and Henane, 1975).This may contribute to the greater body heat content observed in females than males, with a high correlation with onset delay Conversely, some studies using groups of males and females matched for $VO_{2\ max}$, have indicated an equal ability to tolerate heat exposure in males and females, despite differences in the functioning of thermoregulatory mechanisms (Avellini *et al.*, 1980a, Frye and Kamon, 1981; Grucza *et al*, 1985) Women have in fact displayed a physiological advantage during humid heat exposure (Candas *et al.*, 1982; Frye and Kamon, 1983)

The importance of matching subjects for anthropometric, acclimatisation, and fitness parameters is considerable since gender differences in thermoregulation have ceased to be significant upon matching or correction for such factors (Avellini *et al*, 1980a,1980b; Frye and Kamon, 1981, 1983, Havenith and Van Middendorp, 1990, Havenith *et al.*, 1995). In the present study male and female participants have not been matched, reflecting an applied rather than mechanistic approach. 'Typical' sub-elite and elite athletes of both genders have been selected from both groups, whilst recognising that the male athletes are heavier, taller, have a greater SA, lower body fat percentage, and higher $VO_{2\ max}$ than their female counterparts. These factors and their relevance to differences in GSL, regional SR, and T_{core} between sexes will be discussed during the course of this chapter

The present study aimed to produce a whole body sweat map of female athletes at two exercise intensities (60% and 75% $VO_{2\ max}$). A comparison with male athlete body sweat mapping data presented in Chapter 4 was performed to explore regional differences in SR and distribution between sexes.

5.2 Methods

5.2.1 Participants

Thirteen female participants (f1-f11, f13-14) were recruited from the student population at Loughborough and Nottingham University. Inclusion criteria for participants were as follows

- Caucasian females
- Age 18-35 years old
- Regular medium/long distance runner (i e. minimum 3 times per week/top club level to elite)
- 10k running time less than 50 minutes
- No current injuries/medical conditions preventing participants running for 60 minutes
- No problem swallowing a radio pill

5.2.2 Methodology

The experimental methodology for body sweat mapping is outlined in detail in Chapter 2. Only the important points will be repeated here The method is almost identical to that for male athletes in Chapter 4, to which these data will be compared. In summary, participants completed a pre-test session in an ambient temperature of 18°C involving anthropometric measurements, skinfold measurements, and a sub-maximal fitness test. Three identical body mapping experiments were performed at 25°C and 50% rh, each measuring sweat over one third of the body (1: torso, 2 legs, 3: arms, hands, buttocks, and feet) T_{core} was monitored continuously during one of the three experiments and recorded at one minute intervals. Sublingual temperature was measured at BL and post testing for all sessions. Experimental order was counter-balanced across participants to prevent any potential order effect, with a minimum of two days between sessions

5.3 Results

5.3.1 Participants

The physical characteristics of participants involved in the female body sweat mapping experiments are provided in Table 5.1. Participant f12 withdrew from the study after completing only one experiment and therefore is not included in the present study.

5.3.2 Environmental Conditions

The mean (±SD) environmental conditions in the temperature controlled room for the body mapping experiments were 25.7 ± 0.4°C and 44 ± 8 % relative humidity. No significant differences were present in conditions between testing for the different body segments

Table 5.1. Participant characteristics for body sweat mapping Weight, gross sweat loss, and running speed are calculated as the overall mean from all experiments completed, displayed in italic

Participant no	Age (yrs)	Height (cm)	Weight (kg)	Surface area (m2)	Body Fat (%)	Predicted $VO_{2\,max}$ (ml kg-1.min-1)	Av. Total gross sweat loss based on mass loss (g)	Av. Total gross sweat loss based on mass loss (g m-2.h-1)	HR at 25 min (bpm)	HR at 55 min (bpm)	Av Treadmill speed intensity 1 (km.h-1)	Av. Treadmill speed intensity 2 (km.h-1)
f1	22	165 0	59 27	1 65	22 8	54 0	363	189	134	160	6 5	9 1
f2	20	157 0	58 78	1 60	19 6	68 0	580	310	133	157	8 6	10 7
f3	21	175 5	65 98	1 80	22 8	62 1	699	332	137	158	7 8	9 9
f4	20	157 0	49 35	1 60	21 9	62 5	422	226	133	154	8 9	11 8
f5	23	155 0	52 43	1 50	15 7	57 0	468	268	134	156	8 2	9 8
f6	19	164 0	52 70	1 56	19 2	43 0	253	139	127	156	6 1	7 5
f7	18	170 5	60 73	1 70	17 4	52 0	370	187	135	161	6 2	8 5
f8	20	176 0	61 13	1 76	15 7	40 5	401	195	135	157	6 7	8 8
f9	21	168 0	66 78	1 75	18 3	62 3	796	389	134	160	9 7	12 2
f10	21	163 0	54 31	1 56	18 8	69 0	682	374	136	155	11 0	13 2
f11	20	162 0	47 19	1 46	8 8	74 3	310	182	138	153	9 9	10 4
f13	21	159 5	61 70	1 65	16 1	67 1	543	283	132	154	10 0	12 1
f14	21	178 0	71 76	1 86	20 0	61 9	993	458	134	158	10 4	12 4
mean ± SD	**21 ± 1**	**165 ± 7.7**	***58 6 ± 7 2***	**1 64 ± 0 1**	**18 2 ± 3 8**	**59 5 ± 10**	***529 ± 225***	***272 ± 103***	**134 ± 3**	**157 ± 3**	***8 5 ± 1.7***	***10 5 ± 1 8***

5.3.3 Core Temperature and Heart Rate

During all experiments some data points were missing due to the telemetry monitor failing to receive a signal from the core temperature pill. Results are therefore presented as the mean T_{core} over the final five minutes of I1 and I2, where all data was available Baseline data was taken as the temperature recorded immediately before commencing I1 Mean T_{core}, heart rate and work rate for each exercise intensity are presented in Table 5 2.

Table 5.2. Mean core temperature, heart rate, and work rate (± SD) at different exercise intensities *** denotes significance at different time points at the p<0 001, and ** at the p<0 01 level

Time point	Tcore (°C)	Heart rate (bpm)	Work rate (%$\dot{V}O_{2\,max}$)
baseline	37.29 ± 0.3	66 ± 13	-
I1 (26-30)	37 83 ± 0.2***	134 ± 3***	61 ± 7
I2 (56-60)	38 06 ± 0 2**	157 ± 3***	72 ± 11***

T_{core} and HR increased significantly from baseline to I1 (p<0 001) and from I1 to I2 (p<0 01) Participant f2 was requested to ingest a core temperature pill for all sessions to assess intra individual variability in T_{core} over the three sessions Mean values of 37 23 ± 0.1, 37 93 ± 0 1, and 38 14 ± 0 2 were observed for BL, I1, and I2 respectively. Mean sublingual temperature (mean of all experiments) increased significantly from 36 6 ± 0 3°C to 39 9°C ± 0 3 from BL to the end of the experiment

5.3.4 Gross Sweat Loss

GSL was calculated for all experiments from the total weight change of each participant and adjusted for fluid consumption and respiratory and metabolic losses (Methodology, equation (2 10). Corrected and uncorrected values for GSL from all experiments are presented in grams per surface area (g m^{-2} h^{-1}) for each participant (Table 5 3) Unless otherwise stated, corrected values for GSL will be used in analysis and discussion.

Large variation in *GSL* was observed both within and between individuals Differences were observed between conditions, with a significantly higher *GSL* observed for the upper body compared to the arms, hands, buttocks and feet (AHGF) experiment ($p<0.01$). Interestingly, median sweat losses were virtually identical over the three sessions (AHGF 237, UB 251, Legs 234) The mean absolute difference between all experiments was 53 ± 48 $g\,m^{-2}\,h^{-1}$, with values ranging from 1 to 198 $g\,m^{-2}\,h^{-1}$. Participants f3 and f14 illustrated particularly large variation in *GSL* across experiments with values ranging from 237 to 382 $g.m^{-2}.h^{-1}$ and 382 to 580 $g.m^{-2}\,h^{-1}$ respectively A similarly large variation was observed between individuals, with a mean *GSL* across all experiments of 182 ± 32 $g.m^{-2}\,h^{-1}$ for participant f11, in marked contrast to 458 ± 107 $g\,m^{-2}\,h^{-1}$ for participant f14.

Considering the significant difference in *GSL* present between experiments, one might consider a correction factor to allow adjustment of regional sweat rates However, each session followed an identical format with exception only to the region of the body to which pads were applied. The *SA* (mean of I1 and I2) and percentage of total body *SA* covered during each experiment was similar, the upper body in fact covering the smallest *SA* Mean values of 0 49 m^2, 0 45 m^2, and 0 33 m^2 were covered, totalling 1.28 m^2 for the AHGF, legs, and UB experiments respectively. The percentage of body coverage was 30 1%, 27.7%, and 20 2% over the three experiments, totalling 78% of the whole body. The order from lowest to highest results of *GSL* and the sum of all regional area weighted *SR* s (all pads) was identical between experiments, suggesting no change in cooling dynamics. On balance it was decided to provide no correction for the significantly higher gross sweat loss during the upper body experiment

The mean (± SD) sweat loss of all experiments was calculated for both exercise intensities (Table 5 4). Corrected and uncorrected values are presented in grams (g) and grams per surface area ($g\,m^{-2}\,h^{-1}$) for each participant *SA* weighted values are presented from the sum of all regional area weighted *SR* s (all pads) *GSL* increased

Table 5.3. Average gross sweat loss (g m^{-2} h^{-1}) over the whole session uncorrected (uc) and corrected (c) for respiratory and metabolic mass loss during all body mapping experiments AHGF arms, hands, gluts (buttocks), and feet experiment, UB upper body experiment, Legs – legs experiment The overall mean, median, and standard deviation of all experiments are denoted by grey shading (▭) ** denotes significance from the upper body session at the p<0 01 level

	AHGF		UB		Legs		mean		median		SD	
Participant	**uc**	**c**	**un**	**c**	**uc**	**c**	**uc**	**c**	**uc**	**c**	**uc**	**c**
f1	216	147	290	219	272	201	259	189	272	201	39	37
f2	401	316	414	330	369	285	395	310	401	316	23	23
f3	310	237	449	377	464	382	408	332	449	377	85	82
f4	291	211	315	233	318	234	308	226	315	233	15	13
f5	342	262	318	234	387	308	349	268	342	262	35	37
f6	160	97	228	160	226	159	204	139	226	159	39	36
f7	234	168	319	251	209	142	254	187	234	168	58	57
f8	221	155	274	206	291	225	262	195	274	206	36	36
f9	467	374	479	390	497	403	481	389	479	390	15	15
f10	466	365	472	370	486	386	475	374	472	370	10	11
f11	240	157	309	218	254	170	268	182	254	170	36	32
f13	395	299	434	337	303	212	377	283	395	299	67	64
f14	502	411	675	580	477	382	551	458	502	411	108	107
mean	**327****	**246****	**383**	**300**	**350**	**268**						
median	**310**	**237**	**319**	**251**	**318**	**234**	***353***	***272***	***318***	***237***	***111***	***103***
SD	**111**	**101**	**120**	**113**	**104**	**95**						

Table 5.4. Average gross sweat loss from all body mapping experiments uncorrected (uc) and corrected (c) for respiratory and metabolic mass loss at I1 and I2 Whole body surface area weighted sweat rate for all regions measured with pads for I1 and I2 *** denotes significance between exercise intensities at the p<0 001 level

	gross sweat loss I1 (g)		gross sweat loss I2 (g)		gross sweat loss I1 ($g.m^{-2}.h^{-1}$)		gross sweat loss I2 ($g.m^{-2}.h^{-1}$)		SA weighted SR ($g.m^{-2}.h^{-1}$)	
									I1	I2
Participant	**uc**	**c**	**uc**	**c**	**uc**	**c**	**uc**	**c**		
f1	180	120	318	243	164	109	387	295	56	118
f2	316	245	421	335	296	230	526	418	108	181
f3	303	233	556	466	252	194	616	516	100	155
f4	214	146	361	275	201	137	451	344	75	156
f5	227	161	383	307	227	162	511	410	83	138
f6	83	27	289	226	80	26	370	289	26	84
f7	187	127	316	243	165	113	372	286	45	114
f8	185	123	352	278	158	105	401	316	60	112
f9	358	275	626	520	307	235	714	593	197	311
f10	374	291	492	391	359	279	629	500	133	198
f11	191	119	266	190	196	122	364	260	61	93
f13	285	203	439	339	260	185	534	413	146	247
f14	448	356	749	637	361	287	805	685	218	279
mean	***258***	***187***	***428******	***342******	***233***	***168***	***514******	***410******	**101**	**168*****
median	***243***	***165***	***386***	***311***	***222***	***154***	***491***	***387***	**83**	**155**
SD	***105***	***96***	***151***	***139***	***88***	***81***	***155***	***144***	**59**	**72**

significantly ($p<0.001$) with exercise intensity with a mean increase over all experiments of 242 ± 76 $g\,m^{-2}\,h^{-1}$ between I1 and I2. Large variation was observed between individuals, ranging from differences of 93 to 530 $g.m^{-2}\,h^{-1}$ between exercise intensities A significant increase was similarly present between exercise intensities for *SA* weighted *SR* ($p < 0.001$), with a mean increase of 67 ± 21 $g\,m^{-2}\,h^{-1}$ A significant difference was present between *GSL* calculated from weight change and *SA* weighted *SR* at both intensities (I1 $p < 0.01$, I2 $p < 0.001$).

5.3.4.1 Gross Sweat Loss and Predicted Maximal Oxygen Uptake

GSL over the whole test period (mean of all body mapping experiments) was plotted against predicted $\dot{V}O_{2\,max}$ for all participants and a regression line fitted (Figure 5 1) Participants f11 and f14 appeared as outliers, with studentised residuals of -2.10 and 2 07 respectively When considering leverage f14 demonstrated a value of 0 005 compared to 0 182 for f11 Due to the relatively small impact of f14 on the data, the regression line in Figure 5.1 excludes f11 only. Participant f11 is presented with a different symbol from the remaining data and analysis is stated with and without the outlier.

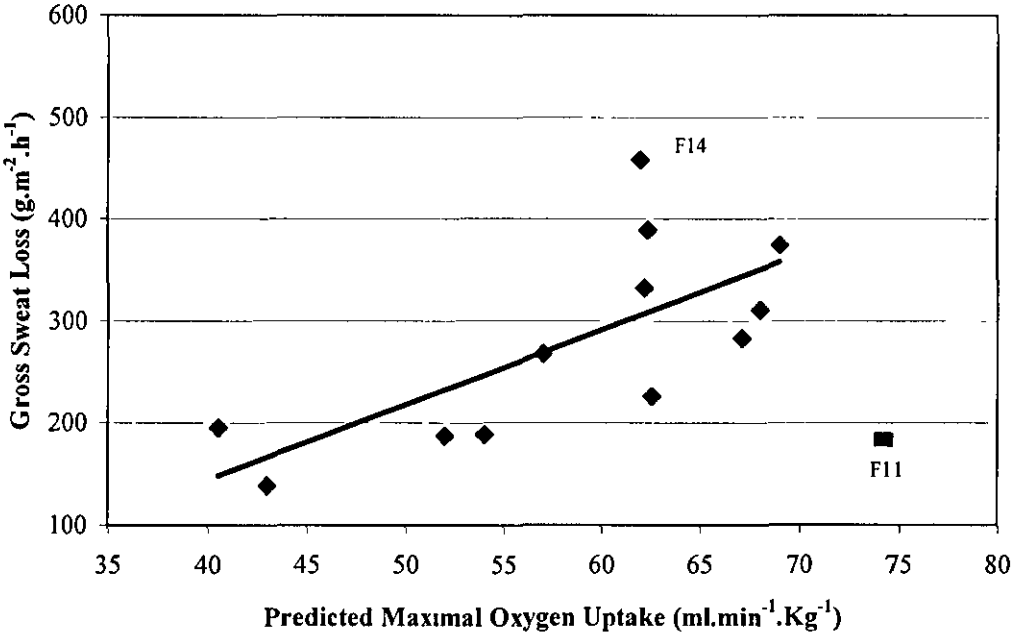


Figure 5.1 Gross sweat loss and predicted $VO_{2\,max}$ for all female body mapping participants

A Pearson's r correlation coefficient of 0.49 shows a non significant, weak correlation between gross sweat loss and $VO_{2\,max}$ in female athletes for the experimental conditions used. In the absence of participants f11, a correlation of 0.71 demonstrates a significant positive correlation between gross sweat loss and $VO_{2\,max}$ ($p < 0\ 01$).

5.3.4.2 Gross Sweat Loss and Metabolic Rate

As a result of secondary analysis of *GSL* and $VO_{2\,max}$ in male athletes within the discussion of Chapter 4 (4 5 2. Gross Sweat Loss), the same analysis has been performed on the female data within the results. Mean *GSL* (all experiments, g m^{-2} h^{-1}) was plotted against metabolic rate (W m^{-2}) for I1 and I2 (Figure 5.2)

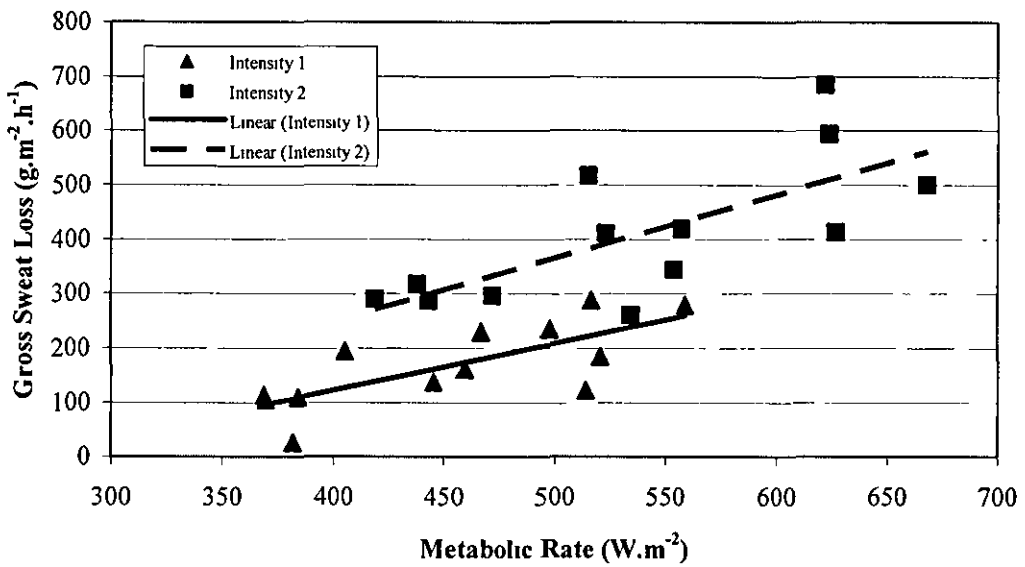


Figure 5 2 Mean Gross sweat loss and metabolic rate for all female athletes at I1 and I2

A significant positive correlation was observed between *GSL* and metabolic rate at both exercise intensities (I1, r = 0.74, p<0 01; I2, r = 0.72, p<0 01). This indicates that the female athletes working at a higher absolute exercise intensity were sweating more than those working at a lower metabolic rate There was no significant difference in the gradient of the two regression lines, suggesting no change in sweating efficiency between the exercise intensities.

5.3.4.3 Gross Sweat Loss and Core Temperature

Mean *GSL* from all experiments was plotted against mean T_{core} from I1 and I2 for all participants (Figure 5 3). Participant f14 had a studentised residual value of 2 16 indicating it as an outlier, however the leverage value was 0.02, suggesting little influence on the regression line Participant f14 was therefore not excluded from analysis

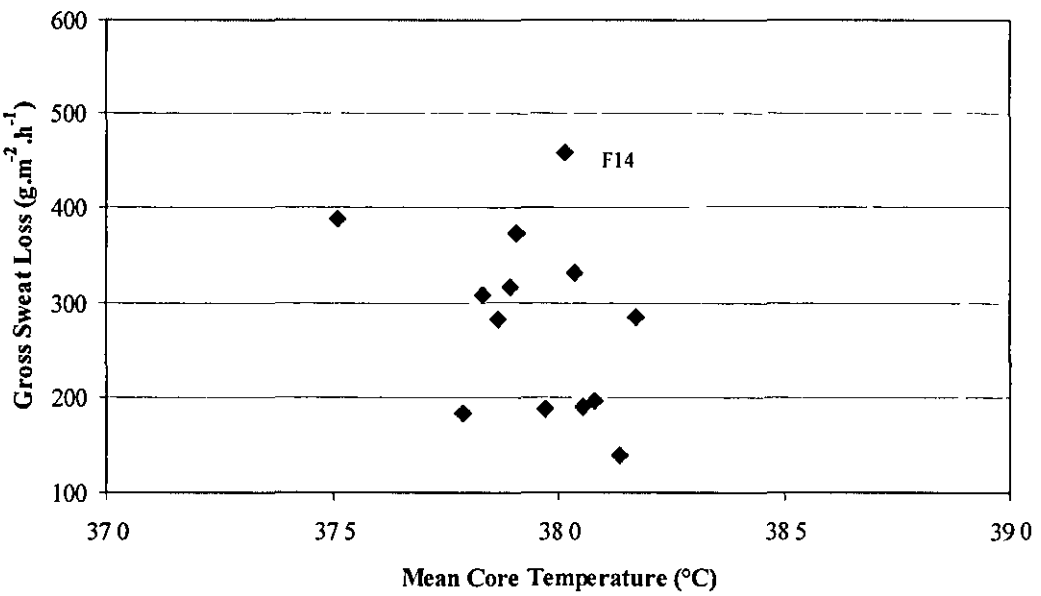


Figure 5.3. Mean gross sweat loss (g m^{-2} h^{-1}) of all experiments and mean core temperature

A Pearson's r correlation coefficient of -0 358 indicates a non significant correlation between mean *GSL* and mean T_{core} in female athletes in the experimental conditions used Notably, the coefficient is clearly being determined by the single data point at 37.5°C.

5.3.5 Regional Sweat Rate

Regional *SR* data were analysed for differences in corresponding right-left zones. Paired t-tests were performed on all relevant zones and Bonferroni correction was applied to adjust for multiple comparisons. A small number of right-left zones were significantly different at the 0 05 level of significance, however these differences were not consistent across exercise intensities nor apparent following Bonferroni correction.

At I1 no right-left differences were present and only the right and left medial upper legs were significantly different at I2 A small number of significant differences were present between the fingers and thumbs and these were subsequently grouped separately. No significant differences were present following Bonferroni correction. Regional *SR* data were grouped for right and left corresponding zones at I1 and I2 for all further analysis. Median right-left grouped data for all participants is illustrated for both exercise intensities in Figure 5 4 and Figure 5 5 respectively

A number of patterns in regional *SR* s were observed in the majority of participants

- Increase in gross and regional SR with exercise intensity
- Upper and central posterior torso showed some of the highest sweat rates over the body at both I1 and I2
- Lowest *SR* s observed on breasts and mid anterior torso
- The bra triangle (medial chest) showed significantly higher *SR* s than the breasts, with the highest *SR* on the body at I2.
- Feet showed little or no increase in sweat rate from I1 to I2
- Significant decrease in *SR* from medial to lateral across posterior torso
- Few significant right-left differences in corresponding zones
- Significant increase from proximal to distal regions on the arms

To allow easy identification of 'high' and 'low' sweat regions and to standardise data over participants, data were normalised for the area weighed *SR* of all individuals and then an average of all individuals was taken. Normalised sweat data for I1 and I2 are illustrated in Figure 5.6 and Figure 5.7. The lowest *SR* were observed on the breasts at I1 and I2, with median values (Inter quartile range, IQR) of 23 (49), 0 (17), 0 (26), and 0 (8) $g.m^{-2}.h^{-1}$ for the medial upper, lateral upper, medial lower and lateral lower breast respectively at I1. Regional *SR* on the breasts increased significantly with exercise intensity in all but one region, with values of 154 (224), 49 (150), 62 (189), and 0 (17) $g.m^{-2}.h^{-1}$ at I2 The palms showed a similarly low *SR* of 38 (73) at I1 and a slight increase to 42 (19) at I2. The highest values were consistently observed on the posterior torso, in particular on the posterior medial upper and medial mid regions *SR* s of 247 (152) and 137 (201) were observed for these regions respectively at I1, and increased

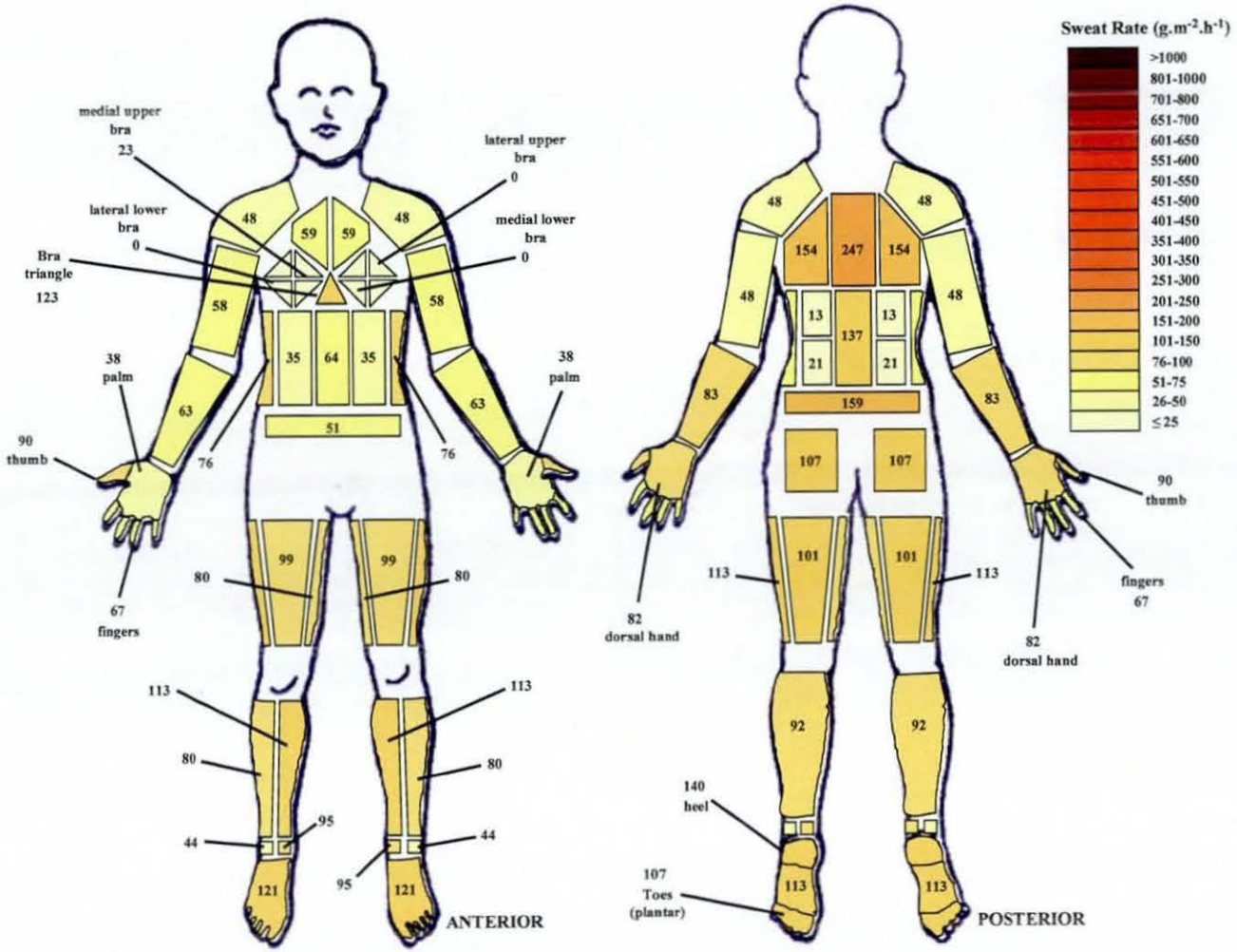


Figure 5.4. Median absolute sweat rate data ($g.m^{-2}.h^{-1}$) for I1.

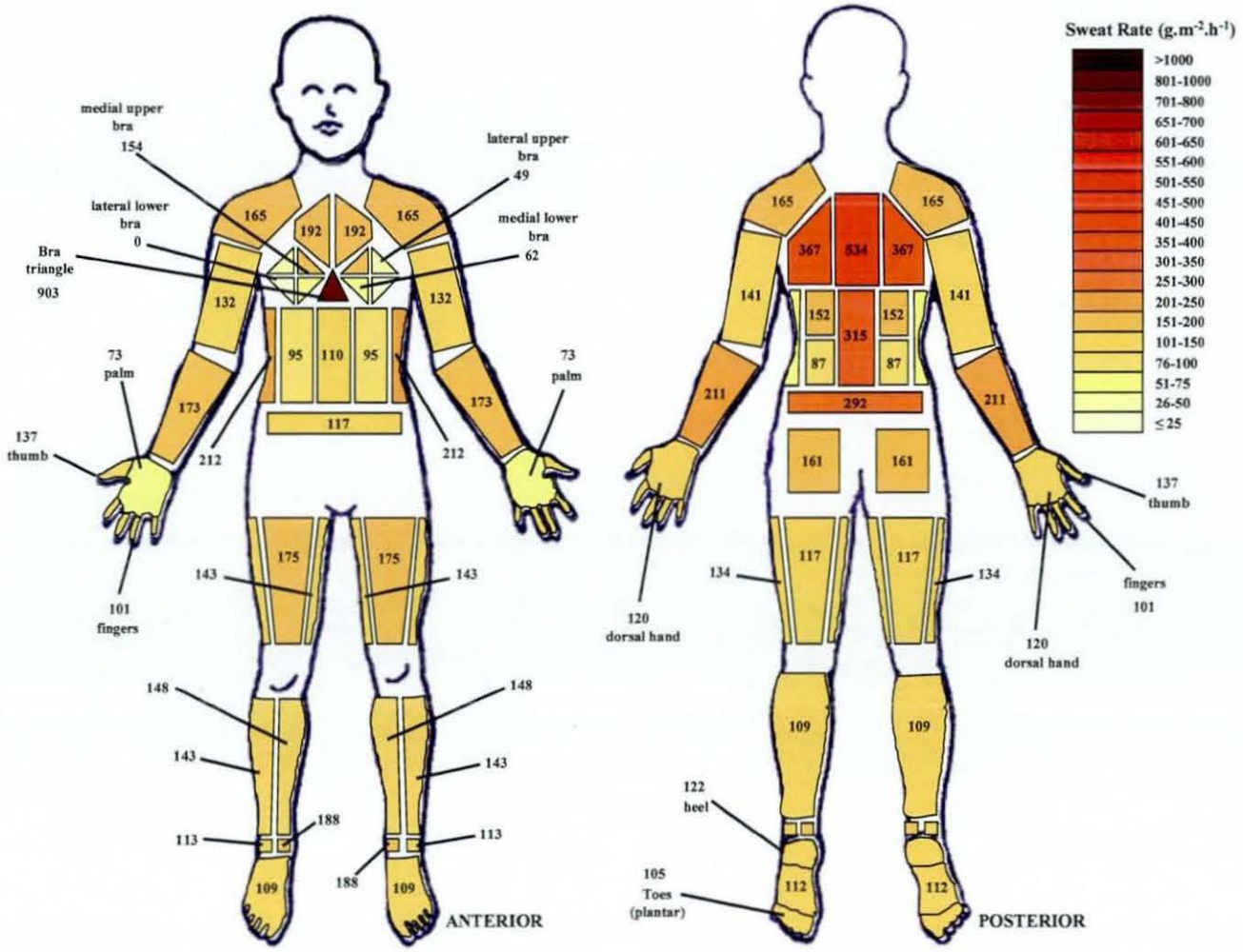


Figure 5.5. Median absolute sweat rate data ($g.m^{-2}.h^{-1}$) for I2.

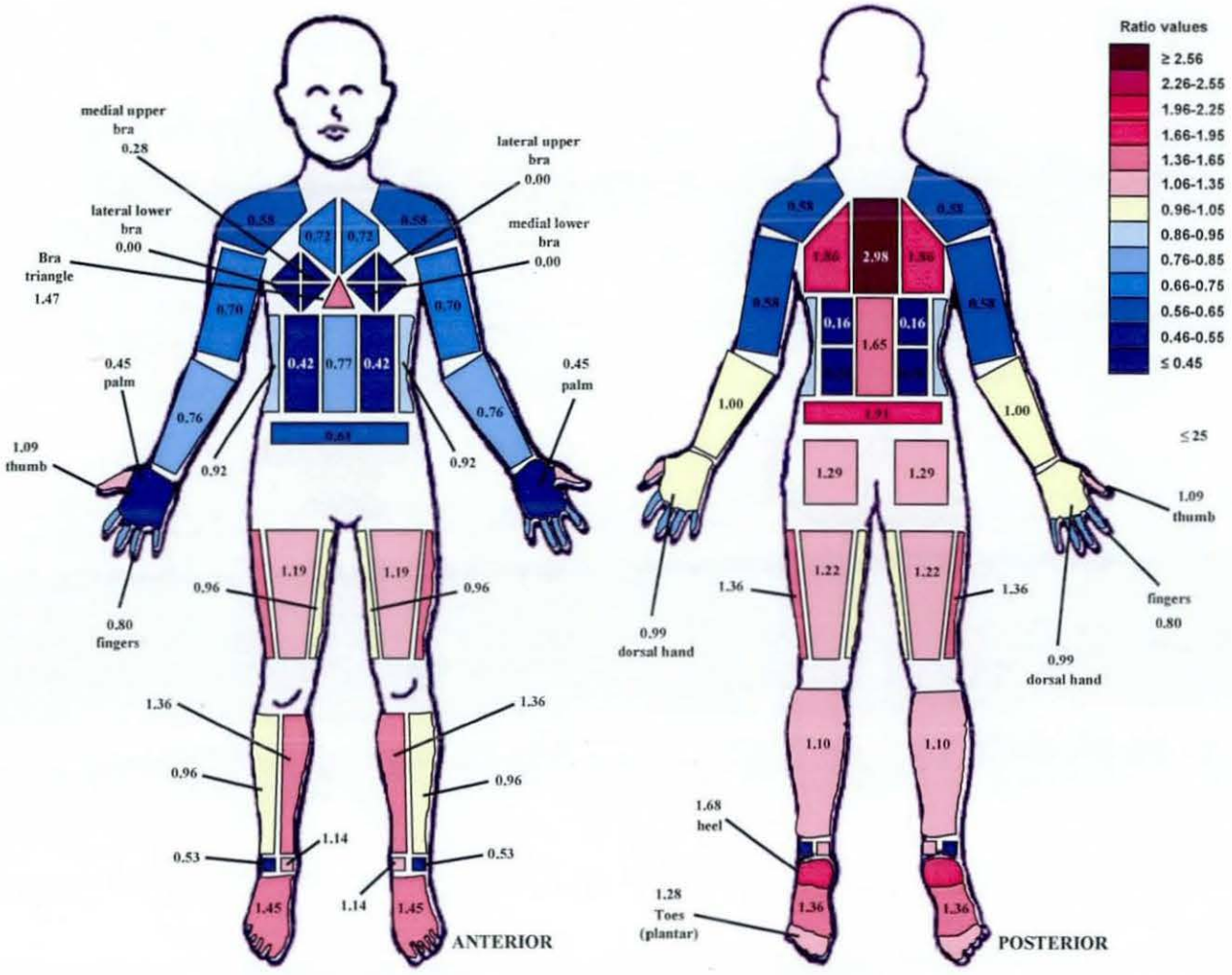


Figure 5.6. Normalised median sweat rate data for female athletes at I1. A value of 1 indicates a sweat rate equal to the area weighted median sweat rate of all regions measured. Values above or below 1 indicate sweat rates higher or lower than the area weighted median sweat rate of all regions measured respectively.

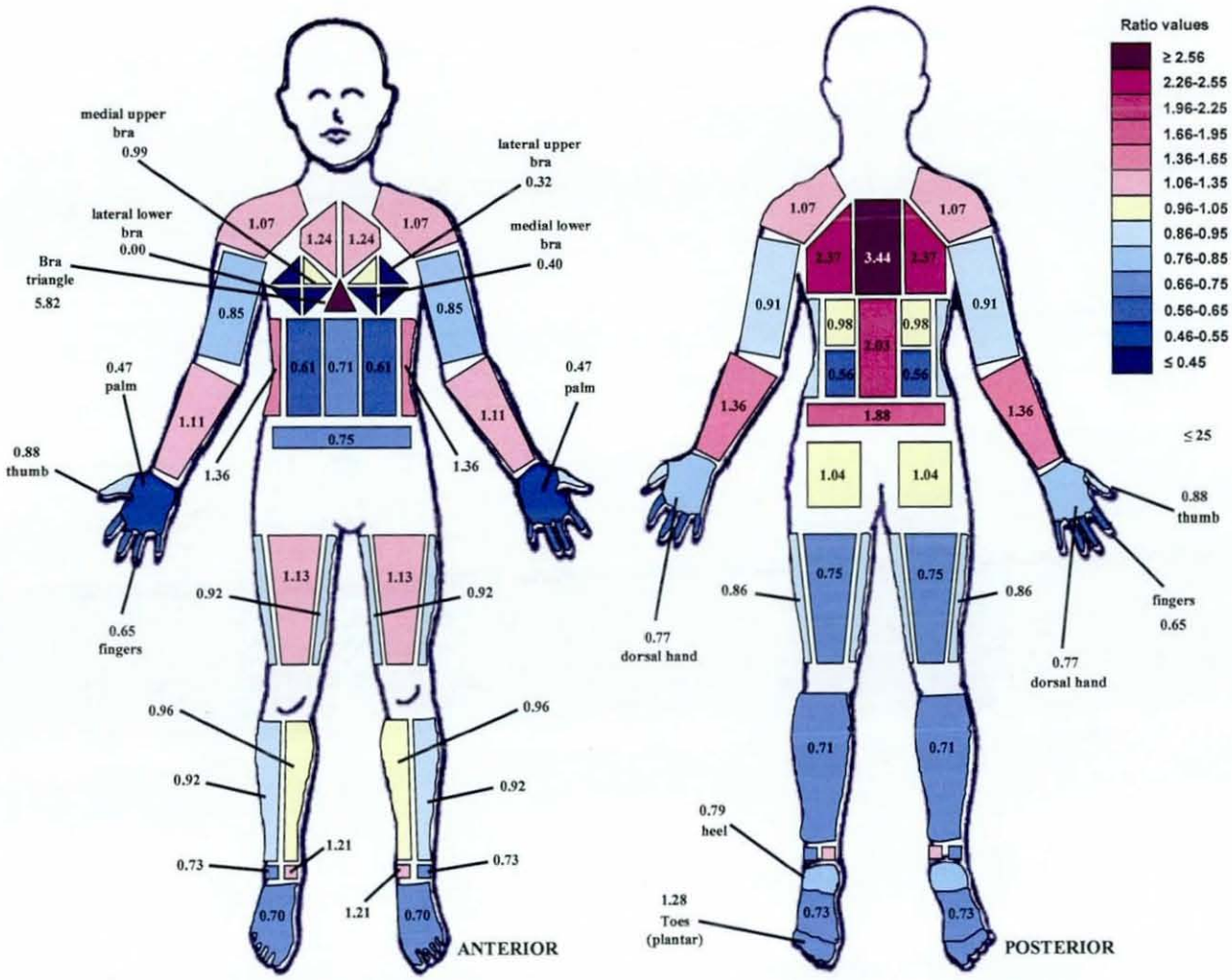


Figure 5.7. Normalised median sweat rate data for female athletes at I2. A value of 1 indicates a sweat rate equal to the area weighted median sweat rate of all regions measured. Values above or below 1 indicate sweat rates higher or lower than the area weighted median sweat rate of all regions measured respectively.

significantly to 534 (317) and 315 (261) at I2. The only exception to these high-low regions was the bra triangle (between the breasts) showing the highest *SR* on the body at I2 with a median value of 903 (749). These high sweat regions are clearly evident in the normalised data with values of 2.98 and 1 65 for the posterior medial upper and posterior medial lower regions respectively at I1 An increase to 3 44 and 2 03 respectively are present at I2, with the bra triangle showing the highest value of 5 82

Surprisingly, the arms and legs had a greater *SR* than the breasts (excl. bra triangle) and mid anterior torso, which consistently showed low *SR* at both exercise intensities. The highest value on the anterior torso was the bra triangle with a *SR* of 122 (469) and 903 (749) at I1 and I2 respectively, with the latter being the highest value over the body at I2. A medial to lateral decrease in *SR* was observed on the torso. The difference between medial and lateral regions was not significant on the anterior (mid) torso but was significant on the posterior at both exercise intensities (upper back I1p < 0.01, I2 p < 0 001; mid-upper back I1 p < 0.01, I2 p < 0 001, mid-lower back: I1 p < 0 001, I2 p < 0 001). Following Bonferroni correction only a significant decrease from the medial mid back to the lateral mid-lower back (p < 0 05) was present. A proximal to distal increase in *SR* was observed on the arms The increase was significant on the posterior at I1 (p < 0 01) and on both the anterior and posterior at I2 (p < 0 01). No significant increase was present following Bonferroni correction

As expected, *SR* increased significantly with exercise intensity in most regions The feet, ankles and lateral lower bra were an exception to this, showing no significant difference between intensities. *SR* s on the dorsal foot, heel, toes, and sole decreased from I1 to I2. This is clearly indicated by a significant decrease in normalised *SR* on these regions. A comparison of *SR* s within each region from I1 to I2 for both absolute and normalised data was performed using a series of paired t-tests and corrected for multiple comparisons. Data is presented in Table 5.5 both with and without Bonferroni correction and states descriptive statistics for all regions tested. The large variation in absolute *SR* between participants was evident from the difference in minimum and maximum values The mean and median are notably different in most regions due to extreme values, highlighting the importance of using median values in analysis

Table 5.5. Descriptive statistics for all regions sampled at I1 and I2 in female athletes A comparison of regional sweat rates between exercise intensities for both absolute and normalised data, corrected and uncorrected for multiple comparisons A decrease in median sweat rate between intensities is indicated by grey shading (r 3)

	Absolute sweat data (g m^{-2} h^{-1})										Significance level of intensity comparison	
	I1					I2						
	min	max	median	mean	SD	min	max	median	mean	SD	Absolute data	Normalised ratio data
shoulders	4	262	48	84	85	75	571	165	208	132	**$	*
upper chest	0	297	59	67	79	53	474	192	198	129	***##	***#
med upper bra	0	117	23	33	40	0	403	154	161	146	**	*
lat upper bra	0	85	0	17	31	0	222	49	79	80	**	**
med lower bra	0	97	0	18	29	0	362	62	98	116	*	-
lat lower bra	0	61	0	7	17	0	81	0	17	29	-	-
bra triangle	0	2257	122	433	667	0	3951	903	966	1032	**$	-
lat mid chest	0	266	35	61	75	21	279	95	121	80	**$	-
med mid chest	0	183	64	74	63	40	285	110	145	85	***##	-
sides	27	319	76	105	96	109	347	212	210	88	***#	-
ant lower	0	370	51	84	104	12	486	117	167	133	***#	-
lat upper back	10	481	154	178	147	138	596	367	373	159	***###	**
med upper back	28	839	247	310	252	124	954	534	550	238	***##	-
lat mid upper back	0	304	13	90	119	0	414	152	203	145	**	-
lat mid lower back	0	345	21	74	104	32	427	87	145	137	**	-
med mid back	0	599	137	180	169	52	777	315	377	189	***###	*
pos lower back	0	590	159	181	197	15	713	292	332	216	**$	-
ant upper leg	29	240	99	120	64	41	377	175	185	96	***#	-
med upper leg	33	230	80	98	62	54	293	143	148	75	**$	-
pos upper leg	44	229	101	100	50	62	303	117	140	70	**	-
lat upper leg	65	213	112	116	42	50	343	134	162	88	*	*
ant lat lower leg	14	304	79	116	82	23	320	143	156	89	**	-
ant med lower leg	29	282	113	127	74	28	397	148	188	107	**$	-
pos lower leg	42	202	92	99	49	53	246	109	134	60	**$	*
ant upper arm	0	155	58	74	58	52	271	132	132	72	***###	-
pos upper arm	0	170	48	62	61	16	262	141	126	73	***###	*
ant lower arm	0	282	63	93	89	44	410	173	170	102	***###	*
pos lower arm	0	264	83	96	89	10	378	211	188	114	***#	-
thumbs	16	224	90	106	73	54	533	137	178	129	*	-
fingers	12	123	67	62	36	23	143	101	91	35	**$	-
palms	1	123	38	51	36	14	138	73	71	30	*	-
back hand	9	302	82	108	93	29	297	120	148	89	*	-
gluts	10	256	107	102	67	53	312	161	170	75	**$	-
sole	41	131	113	106	29	39	143	112	106	30	-	***#
dorsal foot	23	152	121	102	42	34	186	109	112	49	-	***#
toes	57	189	107	114	35	28	198	105	106	45	-	***##
heel	48	201	140	131	44	42	181	122	115	41	-	**$
med ankle	11	354	95	132	119	19	352	188	174	88	-	-
lat ankle	0	236	44	83	81	0	275	113	113	66	-	-

For conversion to other units divide by 600 to get mg cm^{-2} min^{-1}, or by 10,000 to get ml cm^{-2} h^{-1}
No correction *P ≤ 0 05, **P ≤ 0 01, ***P ≤ 0 001,
Bonferroni correction # P ≤ 0 05 ## P ≤ 0 05, ### P ≤ 0 001, $ 0 1 > P ≥ 0 05

Due to the exploratory nature of the sweat mapping study, a comparison of all regions within each exercise intensity was performed. As described in Chapter 4 (4 4 6 Regional Sweat Rates), the design was treated as repeated measures since each measurement was performed on the same individual. A repeated measures ANOVA was performed, with and without Bonferroni correction. The significance level of comparisons for all regions are shown uncorrected and corrected in Table 5 6 and Table 5.7 at I1, and Table 5.8 and Table 5 9 at I2.

Table 5.6. Significance levels of comparison of absolute sweat rates for all regions at 11 uncorrected for multiple comparisons

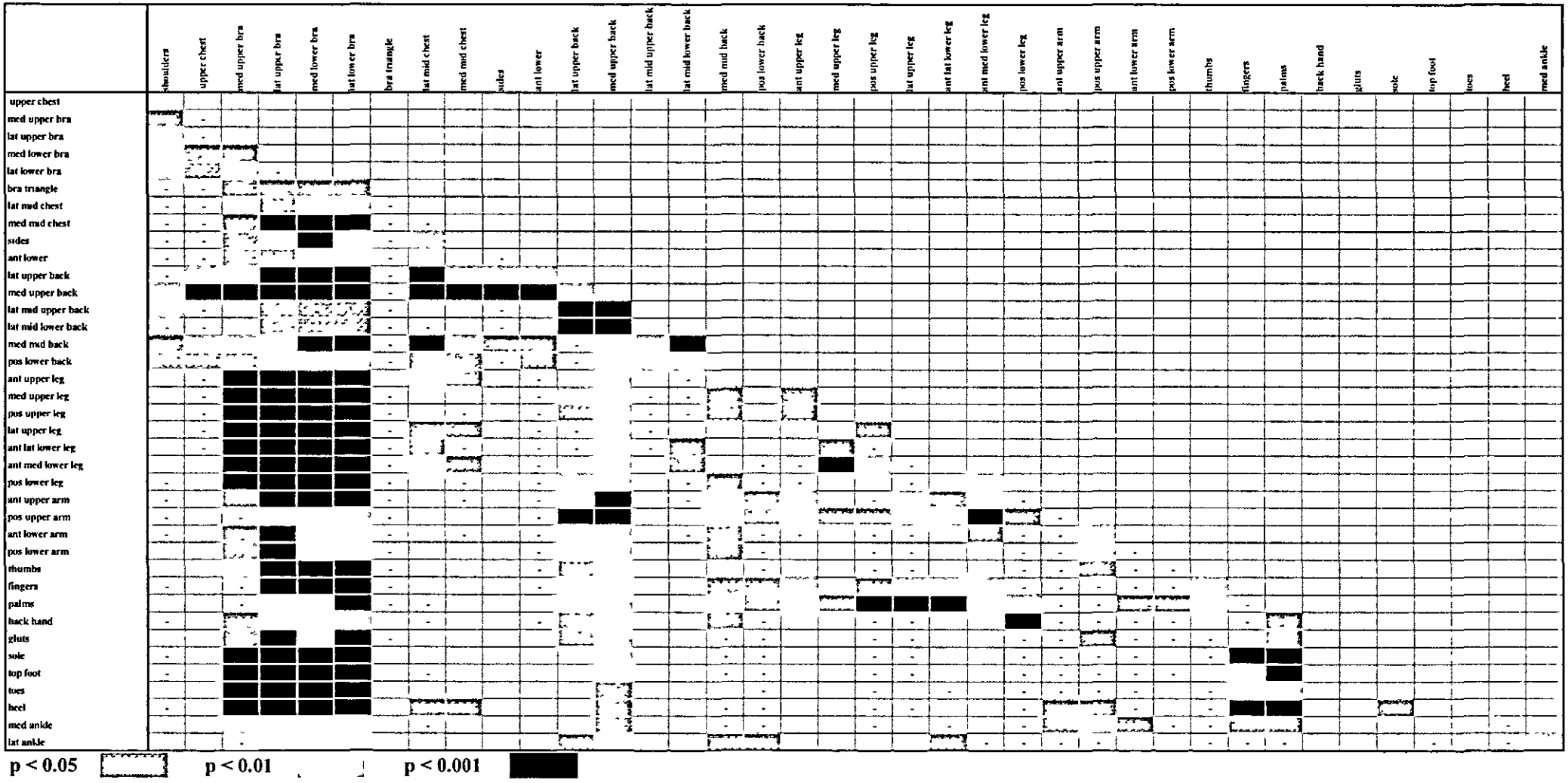


Table 5.7. Significance levels of comparison of absolute sweat rates for all regions at 11 after Bonferroni correction

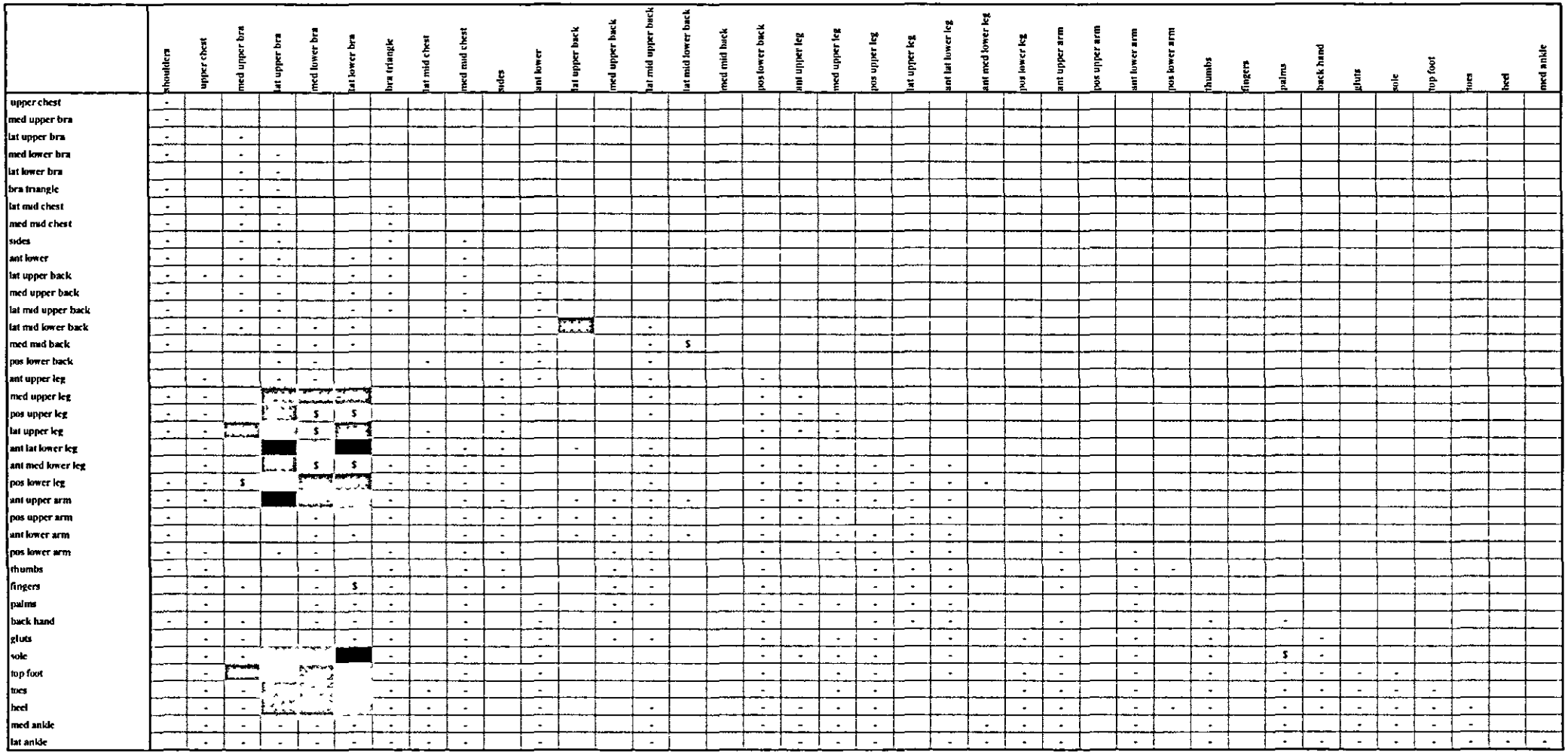


Table 5.8. Significance levels of comparison of absolute sweat rates for all regions at I2 uncorrected for multiple comparisons

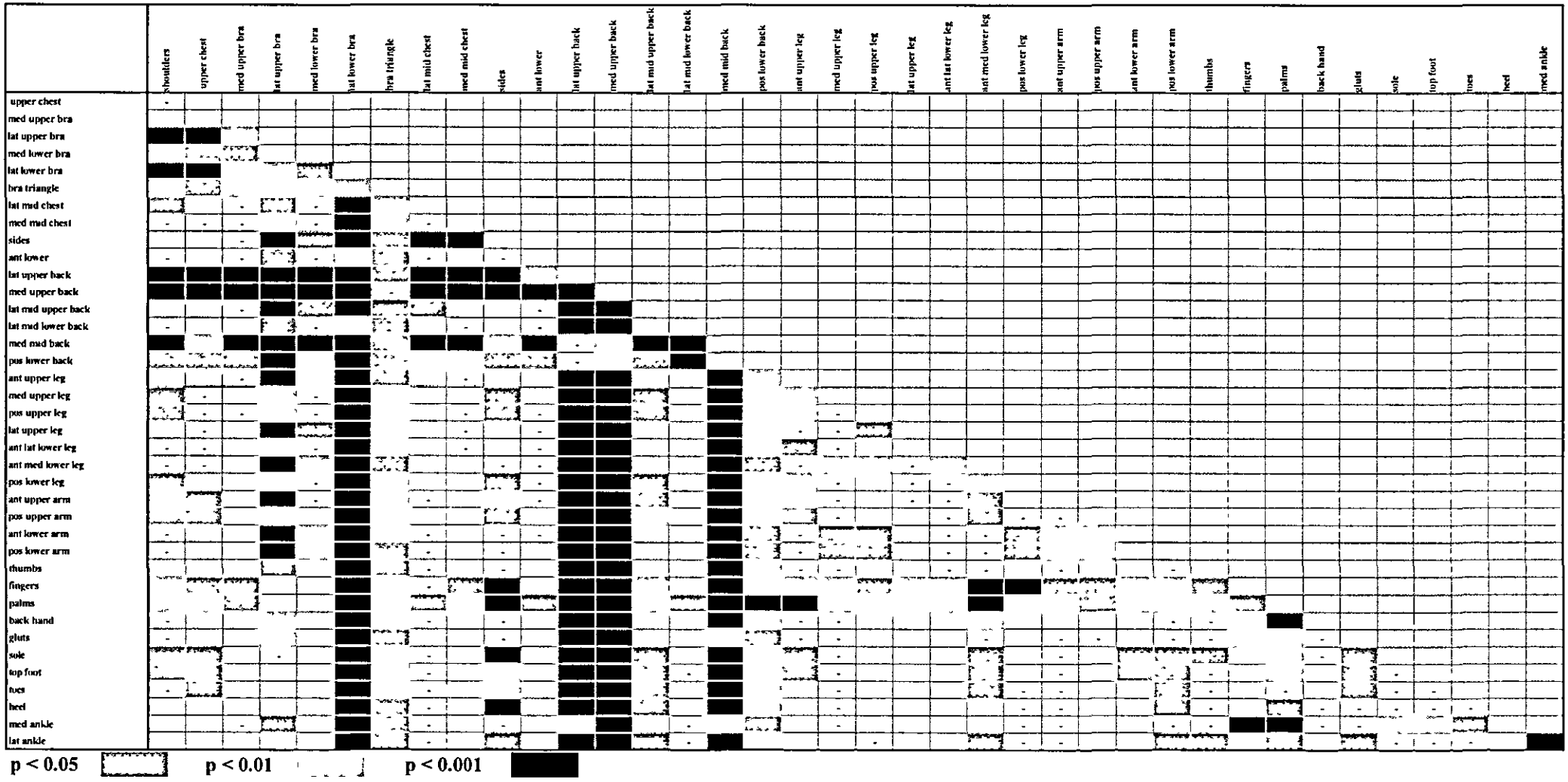
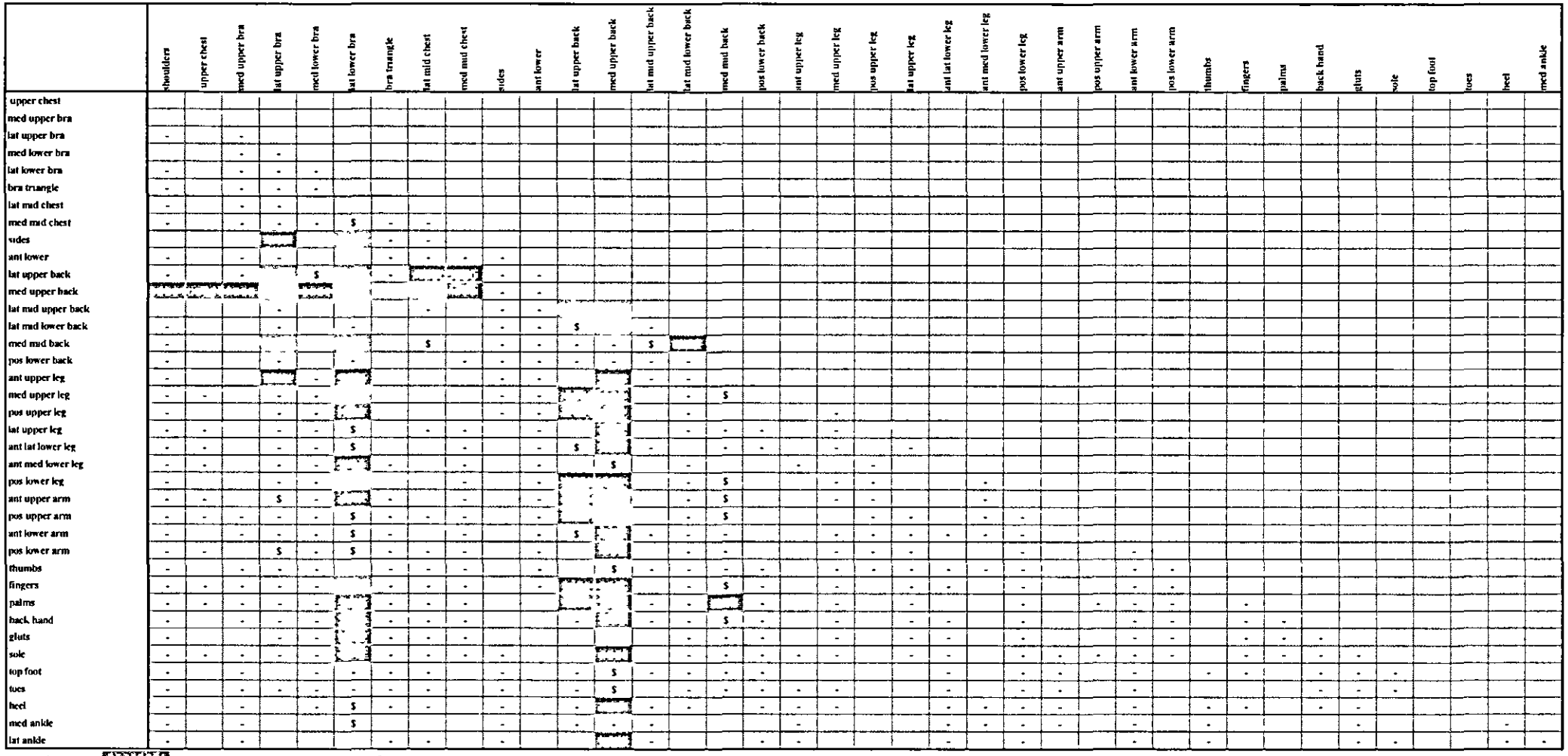


Table 5.9. Significance levels of comparison of absolute sweat rates for all regions at I2 after Bonferroni correction



5.3.6 Regional Skin Temperature

A one-way repeated measures ANOVA and post hoc pairwise comparisons were performed on all regional T_{sk} data for all measurement periods. Significance was present between nearly all medial to lateral regions but was only present in 5 right-left regions (BL: posterior lower leg $p < 0.05$; post I1 pads: anterior lower lateral torso $p < 0.05$, Pre I2 pads posterior lower lateral torso $p < 0.05$, lateral upper leg $p < 0.05$; post I2 pads: anterior upper lateral torso $p < 0.01$) No significant right-left differences were present following Bonferroni correction. As with the male T_{sk} data in Chapter 4, data were grouped for corresponding right-left regions for analysis.

Grouped T_{sk} data at all measurement periods are presented in Table 5.10. Differences between measurement periods were analysed using paired t-tests and corrected for multiple comparisons. Data are presented both with and without Bonferroni correction With exception to the feet and ankles T_{sk} decreased in all regions, albeit not significantly on the legs, posterior arm, and hands. The heels, sole, dorsal foot and ankles increased significantly from BL to pre I1 pad application, reflecting their low baseline values, but showed no further significant change throughout testing The torso was most affected by pad application with a significant increase during application followed by a significant decrease at the next measurement period in all regions except the posterior medial torso (pre I2) The significant decrease in all regions of the torso from BL to pre I1 pad application may reflect the high SR cooling the skin compared to lower SR in other regions.

Regional T_{sk} responded similarly within body segments during sweat mapping Data were grouped further into body segments to provide an overview of T_{sk} responses during testing Figure 5.8 demonstrates the significant increase in T_{sk} at the feet and ankles from BL to pre I1 pad application (feet: 5.4 ± 2.6°C, ankle: 2.3 ± 2.9°C). The anterior torso consistently showed lower T_{sk} compared to the posterior torso Both regions decreased significantly from BL to pre I1 (anterior: 1.9 ± 1.0°C; posterior. 1.8 ± 0.8°C) and showed similar increases with pad application (anterior: I1 1.2 ± 0.7°C, I2 1.2 ± 1.1°C; posterior I1 1.0 ± 0.5°C, I2 1.3 ± 1.0°C)

Table 5.10. Regional skin temperature of female body mapping participants at 5 measurement periods baseline (BL), pre I1 pad application (Pre I1), post I1 pad application (Post I1), pre I2 pad application (Pre I2), and post I2 pad application (Post I2) Significant changes within regions from the previous measurement period are indicated by the symbols listed below the table A significant decrease is indicated by grey shading (.

		Skin Temperature (°C)				
Region		**BL**	**Pre I1**	**Post I1**	**Pre I2**	**Post I2**
UB	anterior upper	34 0	31 8***###	32 7***##	32 1**$	33 1*
	anterior bra (chest)	33 2	31 5***###	32 8***###	31 7***###	33 1***#
	anterior medial lower	32 7	30 3***###	31 8***##	29 8***###	31 2**#
	anterior lateral lower	33 2	31 3***##	32 4***##	31 1***###	32 1**$
	posterior medial upper	34 0	32.3***###	32 9***###	32 7	33 6**#
	posterior lateral upper	33 7	31 7***###	32 9***###	32 1***##	33 5***##
	posterior medial lower	33 4	31 8***###	32 8***##	32 1**#	33 4***##
	posterior lateral lower	32 8	31 1***###	32 2***##	31.1***##	32 5**#
	sides	32 8	31 5***###	32 2***#	31 5**#	32 4**#
Legs	anterior upper	30 7	30 3	31 9***###	30 8*	32 4**#
	medial upper	30 3	30 6	32 5**##	31 4**#	32 7*$
	posterior upper	30 8	30 9	32 5**##	31 2*	32 5**#
	lateral upper	30 7	30 8	32 7**##	31 6**$	33**#
	anterior lower	31 2	30 6	32 0**##	31 3*	32 5**#
	posterior lower	31 0	30 7	32 3**#	31 1*	32 5**##
AHF	anterior upper	32 7	30 7**#	32 4**#	30 9**#	32 4***##
	posterior upper	31 5	31 7	32 3	32 3	33 0*
	anterior lower	32 5	31 0*	32 5**#	31 2**#	32 6**#
	posterior lower	32 2	31 3	32 3*	32 1	33 0*
	palms	31 7	33 0	33 3	33 3	33 7
	hands	30 7	31 3	31 4	31 5	32 0
	heels	26 5	32 3***###	32 7	32 3	33 0
	soles	28 0	34 1***###	34 1	34 3	34 6
	dorsal foot	29 6	33 9***##	34 2	34 4	34 2
	ankles (anterior)	29 9	32 2*	33 0	32 1	32 7
	Mean	**31 7**	**31 5**	**32 6**	**31 8**	**32 9**
	SD	**1.9**	**1.0**	**0 6**	**1.1**	**0.7**

No correction *P < 0 05, **P < 0 01, ***P < 0 001,
Bonferroni correction # P < 0 05, ## P < 0 05, ### P < 0 001, $ 0 1 > P ≥ 0 05

A Pearson's r correlation was performed between regional T_{sk} and regional SR for each participant As described in Chapter 4 (4.4.8. Regional Skin Temperature), within participant analysis was performed due to between participant factors confounding regional skin temperature. SR was compared with both pre and post application T_{sk} measurements separately. No strong correlation was observed at either exercise intensity between SR and pre or post pad T_{sk} The highest r values at I1 and I2 were 0.55 and 0 63 respectively, with the mean r values of all participants of 0 14 and 0 11 at each exercise intensity

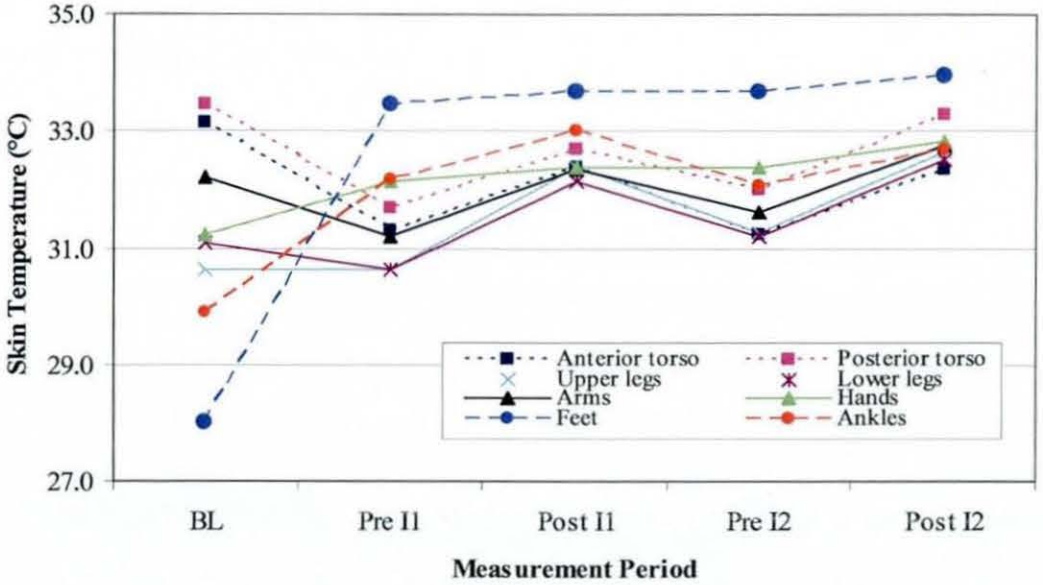


Figure 5.8. Regional skin temperature of female body mapping participants at five measurement periods: baseline (BL), pre I1 pad application (Pre I1), post I1 pad application (Post I1), pre I2 pad application (Pre I2), and post I2 pad application (Post I2).

5.4 Male-Female Comparison

A comparison of the male body mapping data presented in Chapter 4 and the female data presented in the current chapter is discussed.

5.4.1 Participant Characteristics

Females were significantly smaller (male 178.6 ± 4.4cm, female 165 ± 7.7cm), lighter (male 73.40 ± 5 kg, female 58.6 ± 7.2 kg), and showed a higher body fat percentage (male 10.9 ± 4.9%, female 18.2 ± 3.8%) than males ($p < 0.001$). Females had a significantly lower $\dot{V}O_{2\ max}$ ($p < 0.05$), with a value 84% that of male athletes. No significant differences were observed in heart rate between the sexes at either exercise intensity, however males ran at a significantly higher speed at I1 ($p < 0.05$) and I2 ($p < 0.001$).

5.4.2 Gross Sweat Loss

An independent samples t-test was conducted to compare total *GSL* between sexes. Males exhibited a significantly higher *GSL* compared to females ($p < 0.001$) at the same relative work load, with a difference of 44 %.

5.4.2.1 Gross Sweat loss and Maximal Oxygen Uptake

GSL over the whole test period (mean of all body mapping experiments) was plotted against $VO_{2\,max}$ for all male and female participants (Figure 5.9).

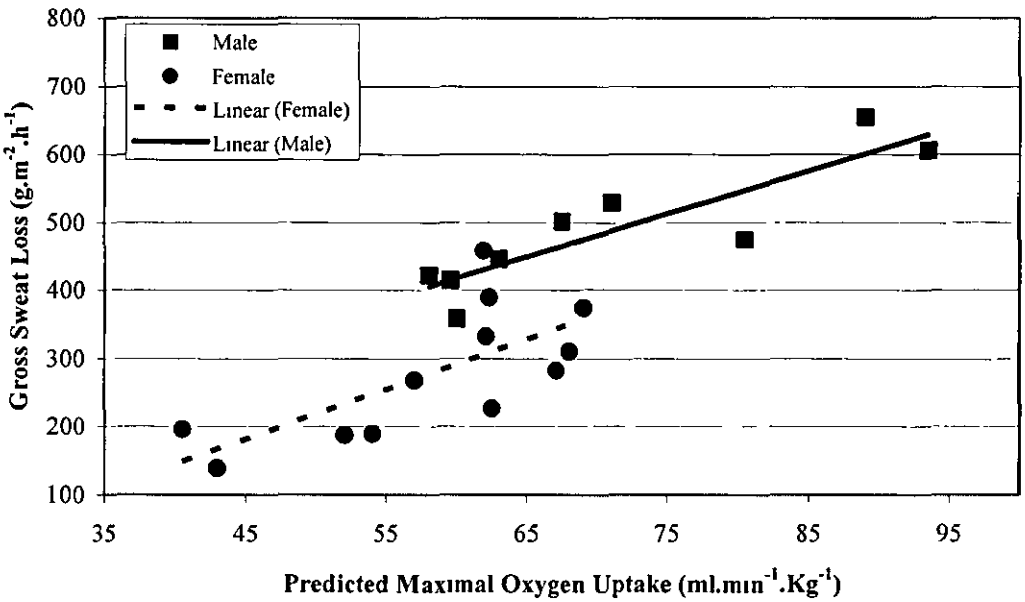


Figure 5.9. Gross sweat loss and predicted $VO_{2\,max}$ for all male female body mapping participants

GSL was higher in athletes with a higher predicted $VO_{2\,max}$, with a significant positive correlation in males ($r = 0.88$, $p < 0.001$) and females ($r = 0.72$, $p < 0.01$) No significant difference was present between the gradients of the regression lines or the intercept between sexes, indicating a similar sensitivity (sweat increase per unit increase in $VO_{2\,max}$). As previously stated, participant f11 was identified as an outlier and removed from analysis

5.4.2.2 Gross Sweat Loss and Metabolic Rate

Mean *GSL* (g m^{-2} h^{-1}) was plotted against mean metabolic rate (W m^{-2}) over I1 and I2 (mean of all body mapping experiments) for all male and female athletes (Figure 5 10 and Figure 5 11).

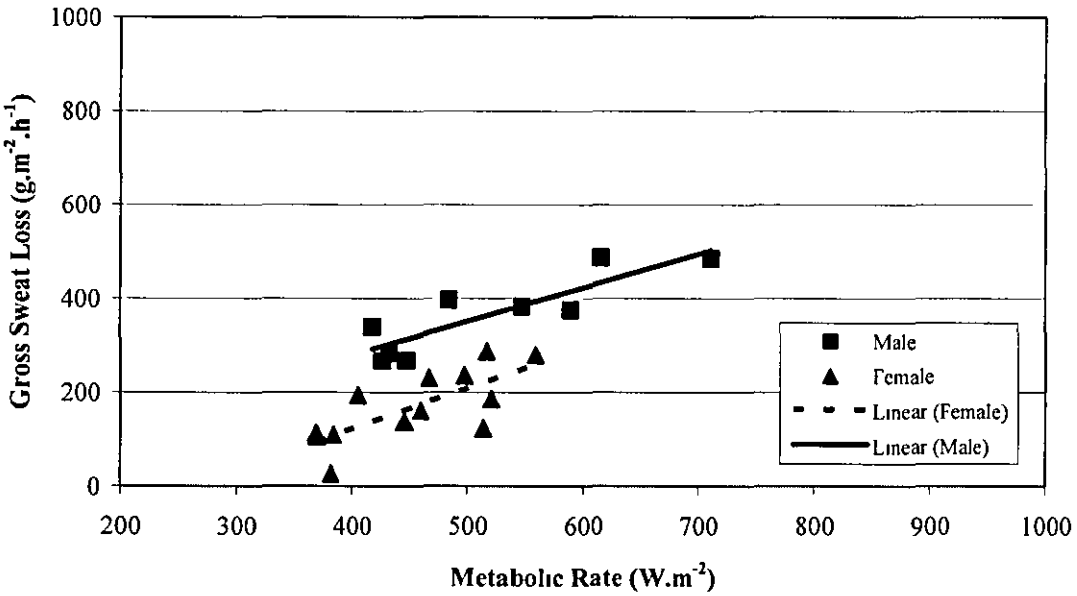


Figure 5.10 Mean Gross sweat loss (g m^{-2} h^{-1}) and mean metabolic rate (W m^{-2}) at I1 for all male and female athletes

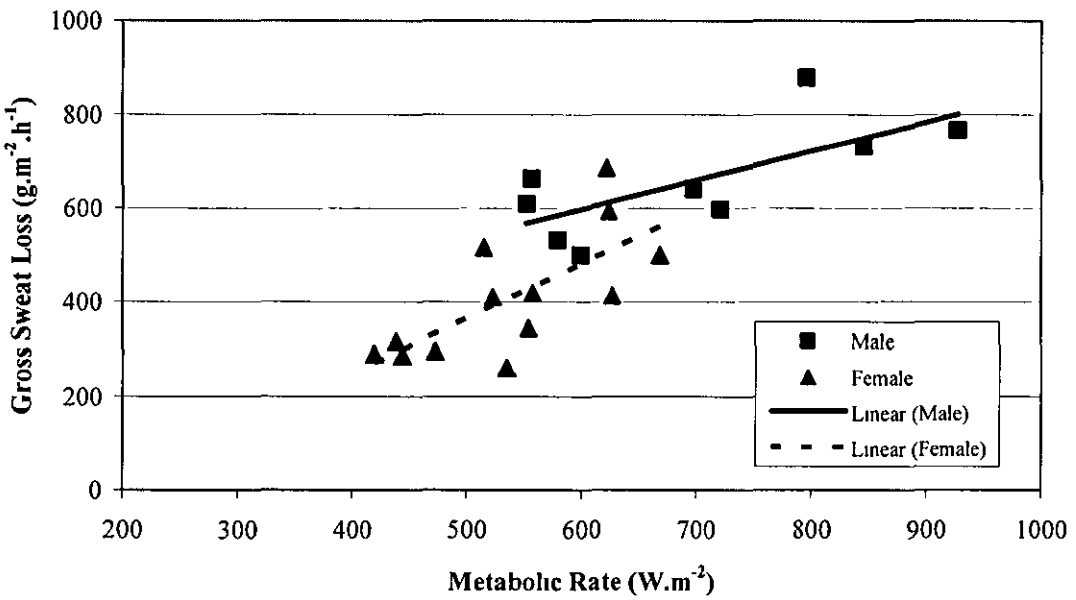


Figure 5.11. Mean Gross sweat loss (g m^{-2} h^{-1}) and mean metabolic rate (W m^{-2}) at I2 for all male and female athletes

Both groups showed a significant positive correlation between *GSL* and metabolic rate (I1. male r = 0.87, p < 0.01, female r = 0.74, p < 0 01; I2: male r = 0 72, p < 0 05, female r = 0.72, p <0.01) There was however no significant difference between sexes in the gradient of the regression lines at I1, nor in the intercept, suggesting the same sweating sensitivity (sweat increase per unit increase in work rate) At I2 female athletes showed a significantly greater regression line gradient (p < 0 05) compared to male athletes, but no difference in the intercept This indicates a greater sensitivity at higher work rates, however this may also indicate a decrease in efficiency compared to males, producing more sweat per unit increase in work rate ($W.m^{-2}$) Males had a significantly higher *GSL* compared to females at both exercise intensities (I1 p < 0 001, I2 p < 0.001) but showed a significantly higher work rate ($W\ m^{-2}$) only at I2 (p < 0 05) Females may be considered more efficient at I1 due to showing the same sensitivity (sweat increase per $W\ m^{-2}$), producing a lower *GSL* for the same metabolic rate, and showing no significant difference in T_{core} from males A difference of 54 $W\ m^{-2}$ was observed between sexes at I1 which although not statistically significant, may be considered biologically relevant. The non significance observed between males and females in metabolic rate may result from the overlap in $VO_{2\ max}$ between groups (Figure 5.9) and large variation in metabolic rate within each group, particularly in the males. Values of 519 ± 103 $W\ m^{-2}$ and 453 ± 66 $W\ m^{-2}$ were observed for males and females respectively at I1, and 697 ± 137 $W\ m^{-2}$ and 538 ± 81 $W\ m^{-2}$ at I2.

When considered in absolute terms, male athletes had a significantly higher metabolic rate (W; p < 0 001) and *GSL* compared to females at both exercise intensities (Figure 5.12 and Figure 5 13). Similarly to the data in Figures 5 10 and 5.11, females showed a significantly greater regression line gradient (p < 0 05) compared to males at I2 only, suggesting a lower sweating efficiency (sweat produced per Watt) compared to males at the higher exercise intensity. There was however a significant difference in the intercepts at both exercise intensities In light of the non significant difference in metabolic rate when normalised for *SA*, males were working at a higher absolute work rate (W) because they were significantly larger than the females (p < 0 001). This is further observed by a non significant difference between sexes when considering *GSL* versus metabolic rate normalised for body mass ($W\ kg^{-1}$). At I1 females therefore demonstrated a lower *GSL* ($g.m^{-2}\ h^{-1}$) for the same metabolic rate ($W\ m^{-2}$ and $W\ kg^{-1}$) as

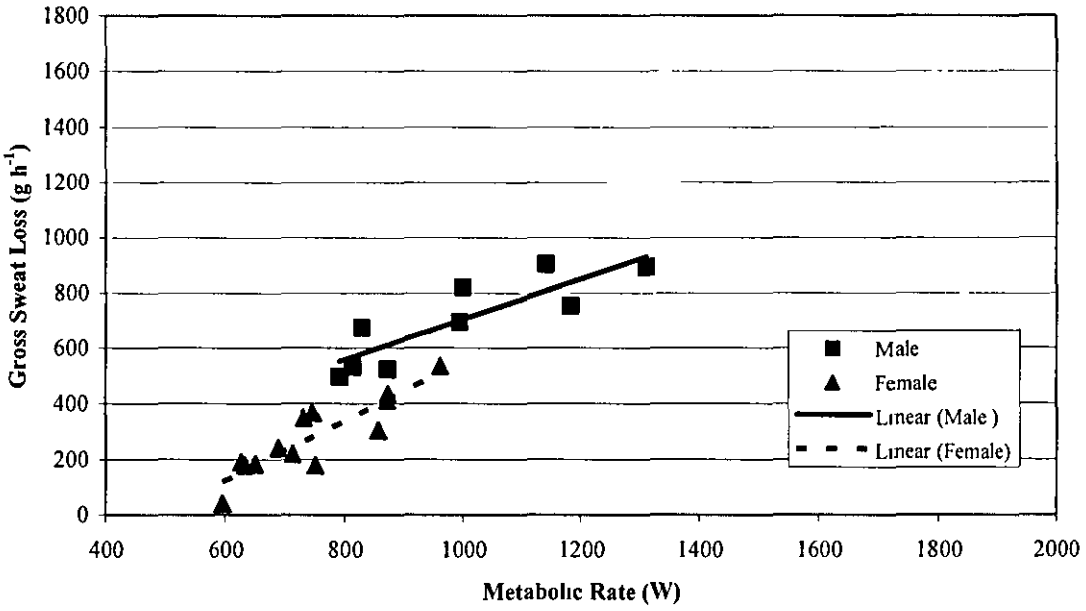


Figure 5.12. Absolute mean gross sweat loss (g h^{-1}) and absolute mean metabolic rate (W) at I1 for all male and female athletes

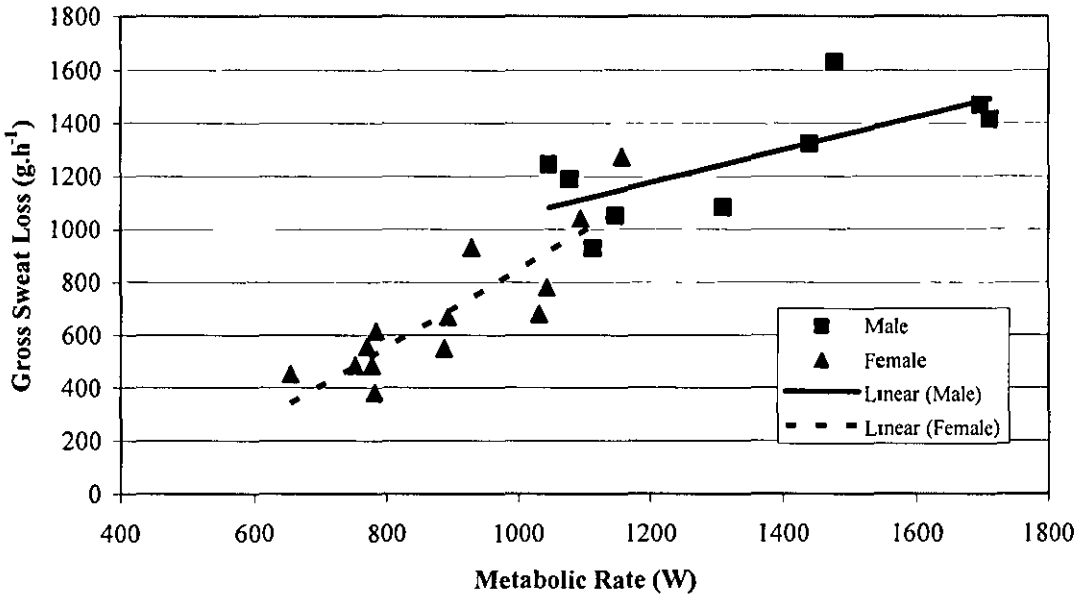


Figure 5.13. Absolute mean gross sweat loss (g h^{-1}) and absolute mean metabolic rate (W) at I2 for all male and female athletes

males. At I2 males had a significantly higher metabolic rate (W m^{-2} and W kg^{-1}) than females and a significantly higher *GSL* (Figure 5.11) Whether females similarly display a lower *SR* than males for an equal metabolic rate at I2, therefore cannot be determined. Females sweated 46% of that of males at I1 and 62% at I2 whilst having a metabolic rate 87% that of males at I1 and 77% at I2.

In terms of heat balance, neither males nor females were producing enough sweat to maintain thermal balance at either exercise intensity, as indicated by E_{req} A calculation of E_{req} was performed using equation (5 1):

$$E_{req} = M - C_{res} - (h_c + h_r) \cdot (\overline{T}_{sk} - T_a) \qquad (5\ 1)$$

Where:

M, metabolic rate (W.m^{-2})

C_{res}, heat loss by respiration (W.m^{-2})

h_c, convective heat transfer coefficient (W m^{-2}.°C)

h_r, radiative heat transfer coefficient (W m^{-2} °C)

C_{res} was taken as 10% of M and h_r was taken as 4.7 W m^{-2}.°C for 'typical indoor conditions' (ASHRAE, 1997). E_{max} was calculated using equation (5 2)·

$$E_{max} = \frac{GSL \cdot 2430}{3600} \qquad (5.2)$$

Where 2430 J g^{-1} is the latent heat of vaporization of water at 30°C and 3600 is time in seconds Based upon these calculations, a heat balance calculation was performed for males and females to determine if *GSL* during testing was adequate to achieve heat balance (E_{req}), and if there were any differences in heat balance between sexes E_{max} was significantly lower than E_{req} for both males ($p < 0\ 001$) and females ($p < 0\ 001$) at I1, however only for females at I2 ($p < 0\ 01$) Calculated E_{max} constituted 62% of E_{req} in males and 43% in females at I1, compared to 94% and 83% for males and females

respectively at I2 Notably, the calculated E_{max} would be in excess of the actual evaporative heat loss since evaporative efficiency would not be 1, causing the difference between E_{req} and E_{max} to be greater than stated. However, what is clear from these calculations is that both males and females do not achieve heat balance during I1, resulting in heat storage and an increase in T_{core}. Since females were achieving less of the required evaporative heat loss compared to males, they may be considered less effective in thermoregulation, however, no significant difference in T_{core} was observed between sexes. At I2 there was no significant difference between E_{req} and E_{max} for the males, with a difference of 26 ± 96 $W.m^{-2}$, compared to a significant difference of 57 ± 62 $W.m^{-2}$ ($p < 0\ 01$) for females. Both sexes achieved a greater percentage of their E_{req} at I2, however heat storage would still occur, as evidenced by the increase in T_{core} during I2 Surprisingly, there was no significant difference in T_{core} between sexes despite the lower percentage of E_{req} achieved by the females

5.4.2.3 Gross Sweat Loss and Core Temperature

Mean *GSL* was plotted against mean T_{core} from I1 and I2 for all male and female body mapping participants (Figure 5.14) Both male and female athletes displayed a non-significant correlation between *GSL* and mean T_{core}. Males showed a lower *BL* T_{core} (male 36.93°C, female 37 29, $p<0\ 05$) but no sex difference was present at the end of each exercise intensity. Increases were significant over both exercise intensities ($p<0\ 001$) in both sexes, but without a significant difference between sexes. An interaction between sex and exercise intensity was present ($p<0\ 05$), reflecting the different *BL* values

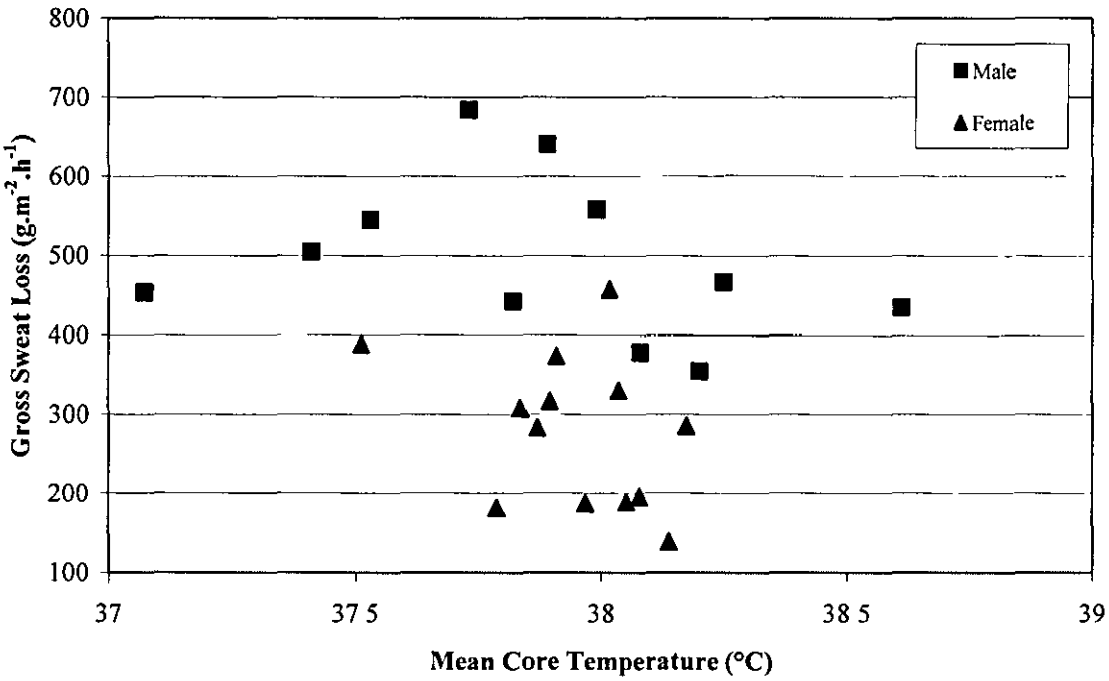


Figure 5.14. Mean gross sweat loss (g m^{-2} h^{-1}) of all experiments and mean core temperature for male and female athletes

5.4.3 Regional Sweat Rate

A significant difference in absolute *GSL* ($p < 0.001$) between males and females has previously been discussed (5 4.2. Gross Sweat Loss).To allow analysis of the distribution in regional *SR* s between males and females, values were produced for both normalised and absolute regional sweat data The design was treated as repeated measures using sex as a between subject factor, allowing a two way repeated measures ANOVA to be performed with sex, region, and sex-region interaction as factors Bonferroni correction was applied to adjust for multiple comparisons, with data presented both corrected and uncorrected (Table 5.11)

A significant main effect of both sex and region were present at both exercise intensities ($p < 0$ 001) in the absolute data, reflecting the significant difference observed in *GSL* ($p < 0.001$). Analysis of the normalised ratio data produced a non significant main effect of sex due to negating the difference in *GSL* and allowing analysis of distribution A significant main effect of region was present in the ratio data at both exercise intensities

($p < 0.001$) in addition to a significant interaction of sex and region (I1 $p < 0.001$, I2 $p < 0.01$). The latter indicates that some regions had higher relative *SR* in males whilst others had higher relative *SR*s in females. Post hoc comparisons were performed to identify differences in distribution, with and without Bonferroni correction (Table 5.11). Sweating in both sexes was greatest on the central posterior torso (spine), and higher on the posterior than the anterior torso. Males illustrated area weighted median values (IQR) of 278 (58) g m^{-2} h^{-1} versus 569 (102) g.m^{-2}.h^{-1} for the anterior and posterior torso respectively (excluding shoulders and sides) at I1 and 462 (158) g m^{-2}.h^{-1} versus 871 (192) g m^{-2} h^{-1} at I2. Similarly females showed area weighted anterior and posterior torso values of 37 (46) g m^{-2} h^{-1} versus 108 (81) g m^{-2} h^{-1} respectively at I1 and 123 (125) g m^{-2}.h^{-1} versus 296 (292) g m^{-2} h^{-1} at I2. Although a similar anterior to posterior sweat pattern is present in both sexes, Table 5.11 indicates that this is the region of most significant difference between the two groups. Males had significantly higher absolute and ratio values on the posterior, whilst females showed significantly lower absolute *SR*s on the anterior torso. The extremities show fewer differences between males and females, both sweating less on the arms and legs in comparison to the posterior torso. The distribution differences do however appear to become less pronounced with exercise intensity, with fewer significant differences present in the normalised data at I2 compared to I1.

Table 5.11. Significance level of male-female comparison of absolute and ratio regional sweat data

	Significance level of male-female comparison			
	Intensity 1		Intensity 2	
	Absolute data ($g\ m^{-2}\ h^{-1}$)	Normalised ratio data	Absolute data ($g\ m^{-2}\ h^{-1}$)	Normalised ratio data
shoulders	***###	**	***#	-
upper chest	***#	*	***#	-
lat mid chest	***###	**$	***###	**$
med mid chest	***#	***###	***###	***#
sides	*	-	**$	-
ant lower	**###	-	***#	-
lat upper back	***###	*	***###	-
med upper back	***#	-	***#	-
lat mid upper back	***###	**$	***###	*
lat mid lower back	***#	***###	***###	**
med mid back	***###	**	***###	-
pos lower back	**$	**	**	-
ant upper leg	*	**	**	*
med upper leg	*	*	*	**
pos upper leg	*	*	*	-
lat upper leg	**	-	*	-
ant lat lower leg	**$	-	***#	-
ant med lower leg	**	-	***#	-
pos lower leg	***#	*	***#	-
ant upper arm	*	-	**	-
pos upper arm	*	-	*	-
ant lower arm	**	-	***###	-
pos lower arm	*	-	***#	-
thumbs	*	*	*	*
fingers	*	*	**	*
palms	**	-	**	*
back hand	-	-	*	*
gluts	**	-	*	-
sole	**	*	***###	-
top foot	**	-	**$	-
toes	*	**	***#	*
heel	*	**$	**	*
med ankle	**	-	**	-
lat ankle	*	-	**	-

For conversion to other units divide by 600 to get mg cm-2 min-1, or by 10,000 to get ml cm-2 h-1

No correction *P < 0 05, **P < 0 01, ***P < 0 001,

Bonferroni correction # P < 0 05, ## P < 0 01, ### P < 0 001, $ 0 1 > P ≥ 0 05

5.4.4 Regional Skin Temperature

Male and female regional T_{sk} were compared at each measurement period using a series of independent t-tests and adjusted for multiple comparisons with Bonferroni correction No significant differences in regional T_{sk} were present between sexes at any measurement period except BL T_{sk} was significantly higher in females in all regions of the torso (pos med upper, pos lat upper $p < 0.05$; ant upper, ant med lower, ant lat lower, pos med lower, pos lat lower $p < 0.01$, sides $p < 0.001$) The posterior medial upper, posterior lateral upper, anterior medial lower and posterior lateral lower regions failed to show significance following Bonferroni correction. No further significant differences were present at BL.

5.5 Discussion

5.5.1 Core Temperature

A significant increase in T_{core} was observed from baseline to I1 ($p<0.001$) and from I1 to I2 ($p<0.01$) in female athletes The results are consistent with those of the male athletes in the current series of studies, who exhibited a similar increase in T_{core} with exercise intensity. The discussion of thermoregulatory mechanisms eliciting the observed increase in T_{core} will therefore not be repeated, but may be referred to in more detail in Chapter 4 (4.5.1 Core Temperature) Since participants were all exercising at a similar specified relative workload, as expected, no significant differences in T_{core} were observed between sexes (Nielsen, 1938; Havenith et al., 1998) When considering the significant difference in $VO_{2\ max}$ between groups ($p < 0.05$), although working at a similar relative workload, the absolute workload, and therefore heat production, would be higher in males (discussed in Chapter 4.4.2 Gross Sweat Loss) Subsequent analysis of mean T_{core} and mean metabolic rate over both intensities was conducted (Figure 5.15). Participants m8 and f9 were identified as outliers (studentised residual >2, leverage value >2*average leverage value) and so analysis is reported without this data

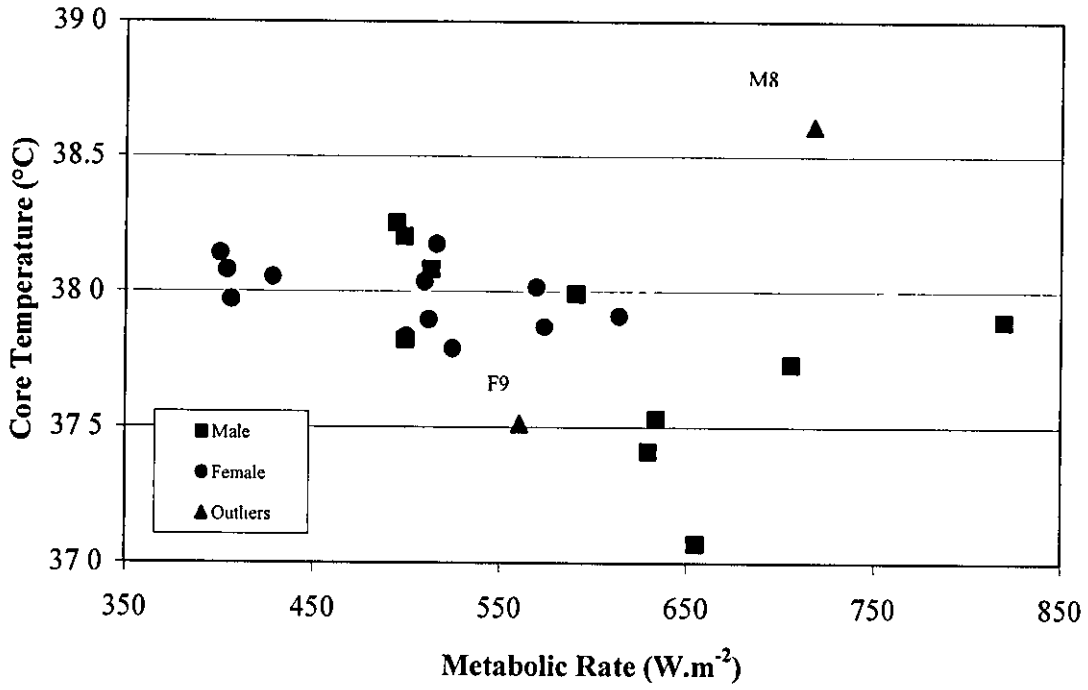


Figure 5.15 Mean core temperature and mean metabolic rate of male and female athletes

Both sexes showed a similar trend, with a moderate, non significant correlation between metabolic rate and T_{core} (exc outliers male r = 0.46, female r = 0 46, incl. outliers: male r = 0.18, female r = 0 49, combined data: incl and excl outliers, r = 0.19) The weak relationship between T_{core} and metabolic rate was unexpected since it is well recognised in literature than an increase in work rate causes an increase in T_{core} Given the similarity in T_{core} and metabolic rate between sexes at I1, it would appear that the female athletes in the current study are able to dissipate heat more effectively than the male athletes at the lower exercise intensity. However, despite working at a significantly higher absolute metabolic rate at I2, male athletes showed no significant difference in T_{core} from females. This suggests that the male athletes became more efficient in heat dissipation at the higher exercise intensity compared to females This is supported by the inability of either group to achieve E_{req} at either intensity, with exception to the males at I2, producing a calculated E_{max} of 94% of E_{req} The suggestion of women regulating body temperature less efficiently than males has frequently been reported, with women exhibiting higher rectal temperature yet lower *SR* s compared to males (Fox *et al.*, 1969, Bittel and Hennane, 1975; Cunningham *et*

al, 1978; Shapiro *et al.*, 1980; Frye and Kamon, 1981) If females were matched for body composition, anthropometric parameters, and fitness level, the superior thermoregulatory abilities of males may be questioned, with the potential for no difference in the ability to dissipate heat between sexes This concept is comprehensively discussed by Gagnon *et al* (2008), who found no difference in the rate of evaporative heat loss between males and females when differences in metabolic heat production were accounted for. Most older studies, use samples of 'average', unmatched males and females in which women are typically smaller, lighter, less fit and have a higher body fat percentage than males, artificially creating sex differences in thermoregulatory function. From the present study, exercising at a workload relative to $VO_{2\ max,}$ female athletes appeared to possess a greater thermoregulatory efficiency at I1 compared to males, producing significantly less sweat for the same T_{core}, but became less efficient compared to males at the higher exercise intensity.

5.5.2 Gross Sweat loss

Considerable variation in *GSL* was observed both within and between female athletes, similar in magnitude to differences in the male athletes (Chapter 4 4 4.5) Similarly to the male athletes, all females in the current study performed their experiments at the same time of day This negates the influence of circadian variation upon intra individual variation in *SR* All experiments were separated by a minimum of 24 hours to eliminate any effects of tiredness or dehydration Menstruation was recorded but not controlled for during this study Data have suggested that T_{core} is elevated by up to 0 5-0 75°C at the time of ovulation, as a result of a thermoregulatory change in set point of the body (Whitelaw, 1952, cited in Stitt, 1993). Others have reported only a small degree of variation with menstruation which may be eliminated through exercise or passive heating (Horvath and Drinkwater, 1982, Frye *et al*, 1982; Inoue *et al*, 2005) The effects of menstruation on thermoregulation were therefore considered as 'background noise', having a minimal affect upon the observed *GSL* during exercise

Similarly to the male athletes in the current series of studies, the correlation between *GSL* and metabolic rate in females results from a difference in absolute work rate since all female athletes were working at similar relative workload. This observation may be

pursued further in explaining the difference in *GSL* between sexes Male athletes had a significantly higher absolute metabolic rate (W) at both exercise intensities ($p < 0.001$). This suggests that the difference in *GSL* between sexes may be attributed to difference in absolute work rate (heat production) rather than an effect of sex per se (Nielsen, 1938; Kenny and Jay, 2007). However, when normalised for body *SA* or weight, metabolic rate was no longer significantly different at I1 yet *GSL* remained significantly higher in males compared to females ($p < 0.001$) For the same normalised metabolic rate females therefore had a lower *GSL* than males. When considering the significantly higher body fat percentage in females ($p < 0.001$), they in fact had a higher metabolic rate per kg lean body mass (muscle) The lower *SR* may therefore indicate a greater sweating efficiency since no significant difference in T_{sk} or T_{core} was present between sexes. The latter is however not unexpected since participants were exercising at the same relative workload. However, when considering the slope of the regression lines for *GSL* ($g\ m^{-2}.h^{-1}$) and metabolic rate ($W\ m^{-2}$), female athletes show a significantly steeper gradient at I2 compared to males, indicating a lower sweating efficiency due to a greater sweat production per unit increase in metabolic rate. Notably, there was no significant difference in the gradient of the regression lines between sexes at I1, supporting females to possess greater thermoregulatory efficiency at the lower intensity due to the lower *GSL*, but becoming less efficient in comparison to males at the higher exercise intensity

Inoue *et al* (2005) found metabolic heat production ($W\ m^{-2}$) to be lower in females than males during passive heating. They concluded that heat loss in women is lower, supported by the significantly lower *GSL*. Since passive heating was used, methodological constraints surrounding matching of exercise level and therefore metabolic heat production between sexes is avoided This is however not without problems. Havenith *et al* (1995) identify the importance of physical characteristics in heat loss responses, with particular reference to body fat, *SA*, mass, and aerobic fitness level. To truly identify sex related differences in sweating, males and females would have to be matched for all the aforementioned parameters. Although useful in a mechanistic approach, this would require an abnormally fit, heavy, and lean female compared to the general population The current study sought to compare regional *SR* s of 'typical' athletes during a 60 minute run in a moderate environment. The lower

regional *SR*s observed may therefore be attributable to both anthropometric and cardiovascular differences between groups. Conversely, Havenith *et al* (2008) compared *GSL* between males and females with no significant difference in $VO_{2\ max}$ but with significantly greater height, weight, and *SA* in the males No significant differences were present in absolute or relative *GSL*, suggesting absolute heat generation to be the greatest factor in determining sweat loss, which for relative work loads is related to $VO_{2\ max}$, with no difference between sexes when matched for fitness level.

5.5.3 Regional Sweat Rate

There is a paucity in thermophysiological research concerning females The majority of studies use male participants, and those which include females generally refer to *GSL* rather than regional *SR* However, in accordance with the large body of literature available on regional *SR*s in males, female athletes in the present study exhibited marked regional variation in *SR* (Weiner, 1945; Kuno, 1956, Hertzman, 1957; Cotter *et al*, 1995; Machado-Moreira *et al*, 2007a,b,c; Havenith *et al*., 2008,) Values were greatest on the medial posterior torso and lowest over the chest and anterior torso. Surprisingly, *SR*s on the arms and legs were greater than those on the breasts and anterior mid torso at both exercise intensities, which is not in agreement with the current literature or the male data presented in Chapter 4. Discrepancies are present in literature regarding differences between males and females with regard to both regional and gross sweat loss. Traditionally, females have been viewed to exhibit lower *SR*s than men whilst maintaining a higher rectal temperature (Fox *et al*, 1969; Bittel and Hennane, 1975; Shapiro *et al*, 1980, Frye and Kamon, 1981, Inoue *et al*, 2005)

Females exhibited greater relative *SR*s on the arms and legs compared to males Since the evaporative heat transfer coefficient is higher on the extremities due to airflow when running, coupled with the larger *SA* to mass ratio in comparison to the torso, heat dissipation is more efficient from the limbs (Inoue *et al*, 2005). This is in agreement with females being more efficient sweaters and therefore displaying a lower *SR* for a given absolute work rate compared to males (Avellini *et al*., 1980a; Frye and Kamon, 1981b). However, the unexpectedly low *SR*s on the anterior torso will have caused the

relative distribution to be greater on the extremities. When compared with data from Havenith *et al* (2008), using the same absorbent technique on the torso as in the current study, similar *GSL* were observed in females with 420 ± 114 $g.m^{-2}.h^{-1}$ versus 410 ± 144 $g\ m^{-2}\ h^{-1}$ (I2) respectively. However, the absolute regional *SR* s on the torso were markedly lower in the present data, in particular on the chest Havenith *et al*, found a median value of 573 $g\ m^{-2}\ h^{-1}$ on the top chest which is over five times greater than the 103 $g\ m^{-2}.h^{-1}$ (area weighted) observed on the chest at I2 in the current study. Notably, the bra triangle showed a median value of 903 $g\ m^{-2}\ h^{-1}$ at in the present study at I2 which was significantly greater than the majority of other torso regions. The females in both experiments had a similar $\dot{V}O_{2\ max}$ (Havenith *et al*· 55 3 ± 6 ml kg^{-1} min^{-1}; current study 59.5 ± 10 $ml.kg^{-1}.min^{-1}$), were running at similar speed (Havenith *et al* 10 8 ± 1 2 km h^{-1}; current study 10 5 ± 1 8 km h^{-1}) and had similar heart rates (Havenith *et al*: 156 ± 11 bpm; current study 157 ± 3 bpm) With exception to the low anterior *SR*, similarities in regional distribution were present between studies The highest *SR* s were on the medial upper and lower back, with values on the posterior being higher than those on the anterior. This distribution was present across all male and female data in the current study and that presented by Havenith *et al* (2008) The latter presented values of 800, 1050, and 720 $g.m^{-2}\ h^{-1}$ fore the medial upper, medial mid, and lower back in females, compared to 1241, 1221, and 939 $g\ m^{-2}\ h^{-1}$ in the present data. Considerably lower values were observed on the arms, with a proximal to distal increase in *SR* in both sexes As discussed in Chapter 4, regional *SR* doesn't correspond well with sweat gland density, however a proximal to distal increase in sweat gland density has been observed on the arms, possibly contributing to the variation in *SR* in that region (Knip, 1969)

The number of sweat glands over the whole body has been estimated at between 2-4 million (Kuno, 1956; Szabo, 1962). Notably, not all sweat glands are active (Ogata, 1935) Some variation in the distribution of functional sweat glands has been observed between sexes, although these differences were not significant (Knip, 1969). The highest densities in both sexes were at the forehead, dorsal hand and dorsal foot, with the lowest values on the legs Males showed a more marked gradient in functional gland density on the arms, increasing from proximal to distal regions Males additionally exhibited a greater density on the lower torso compared to upper regions in comparison

to the more uniform density on the female torso. Females have a higher density of heat activated sweat glands (*HASG*) than males, yet a lower output per gland (Bar-Or *et al* , 1968) Knip (1969) observed *HASG* densities of 91 7 ± 18 0 glands.cm^{-2} and 76.5 ± 14.3 glands.cm^{-2} in males and females respectively. Calculated whole body values were 1.46 ± 0.28 million and 1 47 ± 0 29 million for males and females, giving a smaller total number. The discrepancy between *HASG* density and total values between sexes may be explained in terms of a smaller body surface are in females Bar-Or (1998) suggests that the pattern of smaller and closer sweat drops resulting from a higher gland density may be a more efficient pattern of sweating, despite the lower overall evaporative potential Inoue *et al* (2005) similarly observed a higher number of *HASG* s and lower output per gland during passive heating in females compared to males. Females showed a lower regional *SR* in all regions except the thigh, which was similar to males Heat dissipation on the thigh was greater in women, evidenced by a higher percentage laser cutaneous blood flow on the thigh than in males. This is in agreement with the current data which showed high *SR* s on the legs in females. Inoue et al (2005) suggest that females therefore rely more upon cutaneous vasodilatation than sweating for heat loss compared to men.

On average, women are shorter, lighter, and have a smaller *SA* , yet they posses a larger *SA* to mass ratio than men. This is advantageous for heat dissipation in humid heat, regardless of the high *SR* in males However, during hot-dry conditions, where evaporation of sweat is the greatest avenue of heat loss form the body, females are at a disadvantage. They posses a lower total body water than males and would therefore experience a greater relative dehydration than males if sweat rates were equal. Since the specific heat of water is greater than that of fat, females will experience a greater rate of increase in T_{core} than males working at the same metabolic rate (W m^{-2}) because of their higher body fat percent. Since no significant difference in T_{core} was present between males and females during exercise, yet males showed significantly higher *SR* s, some other modification of regional *SR* must be present Lower regional *SR* in females may result from a lower sensitivity of peripheral thermoregulatory mechanisms. This may reflect sex related differences at the level of the sweat gland through pharmacological sensitivity or variation in sweat gland size Inoue *et al* (2005) observed a lower sweat

gland output (as an index of sweat gland size) in females at the forehead, chest, back, forearm, and thigh.

5.5.4 Regional Skin Temperature

Regional T_{sk} was measured in the present study to asses regional variation over the body and a possible relation with regional SR. The effect of local T_{sk} on both initial SR (Van Beaumont and Bullard, 1965) and its modification of established regional SR is well recognised (Nadel *et al.*, 1971c). It was therefore anticipated that regional T_{sk} and regional SR would exhibit a strong correlation in the current data, contributing to the explanation of the marked variation in regional SR over the body. However, as with the male data presented in Chapter 4, none of the female athletes showed a strong correlation between the two factors. Average r values of all participants for SR correlated with pre and post pad application T_{sk} were 0.14 and 0.16 at I1, and 0 06 and 0.15 at I2. During exercise, no significant differences in T_{sk} were present between sexes at any region in the present data. Similar results have been observed by other authors (Frye and Kamon, 1981b, Inoue *et al.*, 2005) with no difference in regional T_{sk} between males and females. In contrast, Wells (1980) found women to have a higher T_{sk} than men when exercising at the same relative workload, however this experiment was conducted in a dessert setting where solar radiation may have influenced heat balance (Haymes, 1984) Women had significantly higher T_{sk} on all regions of the torso compared to males at baseline in the present study. No 'acclimation period' was used at the beginning of each experiment, making it difficult to compare results both between individuals and between groups

A significant increase in T_{sk} was present in all regions on the torso and legs from pre to post pad application Interestingly, the male athletes in the current study showed the greatest impact of pad application to be the torso, where they also displayed the greatest SR s. In marked contrast, the females showed a similar increase in T_{sk} on the torso with pad application but exhibited the lowest SR s over the body on the chest The female athletes showed a similar increase in T_{sk} to males with pad application with an average increase of 1.1 ± 0 6°C and 1 1 ± 0.5°C at I1 and I2 respectively compared to 0 9 ±

0 5°C and 0 8 ± 0.9°C in males. However, females showed a significant increase over the legs with pad application which was not present in the males The legs exhibited a surprisingly high regional SR in comparison to the torso, which may have been affect to some degree by the rise in T_{sk} from pad application. As discussed in Chapter 4, any methodological effects on the microclimate of the skin were minimised where possible

5.6 Conclusions

The current study aimed to gather regional sweat rate data over the whole body in female Caucasian athletes, and provide a comparison with male data The following conclusions were drawn·

- Large inter and intra regional variation in gross sweat loss was observed in female athletes.
- Considerable variation in absolute regional loss was found between participants yet consistent patterns in regional distribution were present.
- All regions showed a significant increase in sweat rate with exercise intensity, with exception to the feet, ankles, and later lower bra
- Male athletes had a significantly higher absolute gross and regional sweat rate than females at the same relative workload, however similarities in distribution were present
- Highest sweat rates were observed on the medial and lower posterior torso in males and females, with values being greater on the posterior than anterior torso. The females also showed one of the highest sweat rates at the bra triangle
- Few significant differences in distribution were present between sexes however females showed a tendency for greater peripheral sweat rates, suggesting a greater sweating efficiency than males since heat dissipation is more efficient form the limbs
- At I1, females had a similar sensitivity to males (sweat produced per unit increase in metabolic rate), a lower sweat rate for the same metabolic heat production, T_{core}, and T_{sk}, suggesting a greater sweating efficiency.

- At I2, females showed a greater sensitivity compared to males, indicating a lower sweating efficiency due to a greater sweat production per unit increase in metabolic rate. This suggests that female sweat efficiency decreases compared to males at the higher exercise intensity.
- Regional variation in sweat rates over the body could not be explained by regional skin temperature.

Chapter 6

Study 4: Body Sweat Mapping in Untrained Males

6 Chapter Summary

This chapter explores the regional variation in SR in untrained healthy males, and additionally provides a comparison with the male athlete sweat mapping data presented in Chapter 4. A consistent pattern of sweating was present between participants, with the highest SRs observed on the central and lower back and lowest on the extremities, with the notable exception of the feet No correlation was present between regional SR and regional T_{sk} in untrained males. Male athletes had a significantly higher GSL compared to untrained males at both exercise intensities ($p < 0.001$), however regional distributions were similar Limited significant differences in T_{sk} were present between trained and untrained males, but those observed were not consistently higher in either group or consistent across measurement periods No correlation was observed between regional SR and regional T_{sk}

6.1 Introduction

Similarly to the literature available for male and female athletes, sweat data concerning untrained males concentrate primarily on gross sweat loss The limited regional sweat data available typically represent only a small number of sites, each covering a small surface area, predominantly due to the use of a ventilated capsule technique The use of differing experimental protocols, exercise modes, environmental conditions, and sweat collection techniques further complicates the comparison of data between studies Although regional variation in sweating over the body is well recognised (Weiner, 1945, Kuno, 1956; Hertzman, 1957; Cotter *et al*, 1995; Taylor *et al*, 2006, Fogarty *et al*., 2007; Havenith *et al*, 2008; Machado-Moreira *et al*., 2008a; 2008b, 2008c) little work has been conducted to directly compare regional sweat rates and distributions in trained and untrained males. It has commonly been observed that individuals with a

high $VO_{2\ max}$ have a higher gross sweat loss and reduced sweating onset time than untrained individuals (Greenleaf *et al*, 1972, Taylor and Cotter, 2006; Gagnon *et al*, 2008). Repeated bouts of high intensity exercise, which are part of routine training for the athletes, elicit a rise in T_{core} which results in an adaptation similar to that developed through heat acclimation (Nadel *et al*, 1974; Shvartz *et al*, 1974). This produces a more effective thermoregulatory response to exercise and/or hot environments. The question as to whether or not the distribution of sweat is the same between trained and untrained individuals is however unclear The present study was therefore undertaken to produce a whole body sweat map of untrained, healthy males The experimental protocol and sweat collection technique used for male athletes in Chapter 4 were used in the present chapter This allowed a direct comparison of absolute regional sweat data and regional distribution between the two groups.

6.2 Methods

6.2.1 Participants

Six healthy untrained male participants (c1-c6) were recruited from the student population at Loughborough University. Inclusion criteria for participants were as follows:

- Caucasian males
- Age 18-35 years old
- Less than 2 hours of exercise per week, excluding walking/cycling to and from University
- No current injuries/medical conditions preventing participants walking for 60 minutes
- No problem swallowing a radio pill

6.2.2 Methodology

The test procedures were identical to those in Chapter 4 and 5 and are described in detail in Chapter 2. Participants completed a pre-test session for collection of anthropometric data, a sub-maximal fitness test and skinfold measurements (Chapter 2:

2 3 Pre test session). Unlike the seven point calliper method used for male athletes a three point skinfold measurement was used for the calculation of body fat percentage in untrained males due to different subcutaneous and internal fat distributions between groups. Three identical body mapping experiments were completed at 25°C and 50% *rh*. One third of the body was measured for regional *SR* s during each experiment, with the order counter-balanced across participants. Two exercise intensities were performed by walking at differing grades (%) on a treadmill due to the low cardiovascular fitness of the participants. Heart rate would have become too elevated if running and participants would have been unable to complete one hour of running The relative workload was based upon heart rate, matching that of the other studies in this thesis (Chapter 4 and Chapter 5). T_{core} was monitored continuously during one of the three experiments for each participant and recorded at one minute intervals

6.3 Results

6.3.1 Participants

The physical characteristics of the untrained male participants involved in the body mapping experiments are provided in Table 6 1 Large variation in anthropometric measurements were observed between participants In particular, body weight, body fat percentage, and predicted $VO_{2\,max}$ showed values ranging from 59 88 to 90 92 kg, 8.8 to 21 4%, and 33 6 to 51.3 $ml.kg^{-1}\,min^{-1}$.

6.3.2 Environmental Conditions

The mean (±SD) environmental conditions in the temperature controlled room for the body mapping experiments were 25 6 ± 4 5°C and 48 5 ± 0 5% relative humidity No significant differences were present in conditions between testing for the different body segments.

Table 6.1. Participant characteristics for untrained male body sweat mapping Weight, gross sweat loss (± SD), running speed and gradient are calculated as the overall mean from all experiments completed

Participant no.	Age (yrs)	Height (cm)	Weight (kg)	Surface area (m^2)	Body Fat (%)	Predicted $\dot{V}O_{2\,max}$ ($ml\,kg^{-1}\,min^{-1}$)	Av Total gross sweat loss based on mass loss (g)	Av. Total gross sweat loss based on mass loss ($g.m^{-2}\,h^{-1}$)	HR at 25 min (bpm)	HR at 55 min (bpm)	Av. treadmill speed intensity 1 ($km\,h^{-1}$)	Av. treadmill speed intensity 2 ($km\,h^{-1}$)	Av. gradient Intensity 1 (%)	Av gradient Intensity 2 (%)
c1	20	181 0	74 26	1 94	14 4	33 6	458 ± 64	202 ± 28	136	159	6 5	6 5	4 4	6 0
c2	23	181 5	59 88	1 78	8 8	36 8	259 ± 55	125 ± 27	136	157	6 4	6 4	2 8	5 7
c3	20	177 0	84 96	2 02	13 0	39 6	477 ± 125	202 ± 53	132	153	5 8	5 9	2 7	7 7
c4	26	189 0	90 92	2 16	21 4	50 3	728 ± 93	289 ± 37	134	155	5 7	6 0	6 2	7 8
c5	20	179 5	69 61	1 89	9 2	51 3	477 ± 132	216 ± 60	136	157	6 5	6 5	5 2	7 1
c6	24	180 5	85 11	2 04	17 9	44 4	703 ± 56	295 ± 24	127	150	6 6	6 6	4 2	9 7
mean ± SD	**22 ± 3**	**181 4 ± 4 0**	**78 23 ± 12 4**	**1 97 ± 0 1**	**14 1 ± 4 9**	**42 7 ± 7 2**	**517 ± 175**	**222 ± 64**	**133 ± 4**	**155 ± 3**	**6.3 ± 0 4**	**6.3 ± 0 3**	**4.3 ± 1 6**	**7.3 ± 1.4**

6.3.3 Core Temperature

Four of the six control participants (c1, c2, c4 and c6) ingested a core temperature pill during one of their three experiment. Results are presented as mean T_{core} over the final five minutes of I1 and I2 Mean T_{core} over the whole experiment was taken as an average of these values. *BL* data was taken as the temperature recorded immediately before commencing I1. Mean T_{core}, heart rate and work rate for each exercise intensity are presented in Table 6.2.

Table 6.2. Mean core temperature, heart rate, and work rate (± SD) at different exercise intensities *** denotes significance from the previous time point at the p<0 001, ** at the p<0 01 level, and * at the p<0 05 level

Time point	Tcore (°C)	Heart rate (bpm)	Work rate (%$\dot{V}O_{2\,max}$)
baseline	37.40 ± 0 4	83 ± 11	-
I1 (26-30)	37.93 ± 0.5*	133 ± 4***	58 ± 11
I2 (56-60)	38 18 ± 0 6*	155 ± 5***	72 ± 11**

A paired sample t-test indicated a significant increase in T_{core} from both *BL* to I1 and I1 to I2 As expected, heart rate increased significantly from baseline to I1, with both heart rate and work rate increasing significantly from I1 to I2 Sublingual temperature was measured in all participants and showed a non significant mean increased form 36.7 ± 0 3°C to 36 9 ± 0 3°C from *BL* to the end of the experiment This result was surprising given the significant increase in T_{core}. This may have resulted from the cooling of the respiratory tract by saliva evaporation, particularly during exercise, and if the participant did not maintain a sufficiently closed mouth during measurement.

6.3.4 Gross Sweat Loss

GSL was calculated based on the total weight change of each participant and adjusted for fluid consumption and respiratory and metabolic losses (Methodology, equation 2.10) Corrected and uncorrected values from all experiments are presented in grams per

surface area per hour (g $m^{-2}.h^{-1}$) for each participant (Table 6 3) Corrected values for *GSL* will be used in analysis and discussion

As observed in both the male and female athlete data presented in Chapters 4 and 5 respectively, large variation in *GSL* was observed both within and between untrained male participants. A significantly lower *GSL* was observed in the legs experiment in comparison to both the upper body ($p < 0.05$) and AHGF ($p < 0.05$) experiments The mean absolute difference between all experiments was 49 ± 30 g m^{-2} h^{-1}, with individual differences between tests ranging from 2 to 120 g $m^{-2}.h^{-1}$. Such large variation between experiments was demonstrated by participant c5, with *GSL* values ranging from 155 g $m^{-2}.h^{-1}$ to 275 g m^{-2} h^{-1} during the legs and AHGF experiments respectively, reflecting the significantly lower GSL observed in the legs experiment

As discussed in Chapter 5 (5 3 4 Gross Sweat Loss) regarding the female data, a correction factor for the untrained male *GSL* data may be considered in light of the significant difference between experiments. However, the protocol for each experiment was identical with exception only to the region of pad application The *SA* (mean of I1 and I2) covered during each experiment was 0.58 m^2, 0 49 m^2 and 0 38 m^2 for the AHGF, legs, and UB experiments respectively, equating to a total of 73% of the body *SA*

The mean (± SD) sweat loss of all experiments was calculated for both exercise intensities (Table 6 4) Corrected and uncorrected values are presented in grams (g) and grams per surface area (g.$m^{-2}.h^{-1}$) for each participant Surface area (SA) weighted values are presented from the sum of all regional area weighted sweat rates (all pads) A significant increase in *GSL* was present from I1 to I2 ($p < 0.001$) with a mean increase over all experiments of 154 ± 50 g m^{-2} h^{-1}. Large between subject variation was observed for the increase in *GSL* between exercise intensities with values ranging from 89 to 205 g m^{-2} h^{-1}. A significant increase was present between exercise intensities for the SA weighted mean sweat rate ($p < 0.01$), with a mean increase of 53 ± 29 g m^{-2} h^{-1} A significant difference was present between *GSL* calculated from weight change and *SA* weighted *SR* at both intensities (I1 $p < 0.01$, I2 $p < 0.01$)

Table 6.3. Mean gross sweat loss (g m^{-2} h^{-1}) over the whole session uncorrected (uc) and corrected (c) for respiratory and metabolic mass loss during all body mapping experiments AHGF arms, hands, gluts (buttocks), and feet experiment, UB upper body experiment, Legs – legs experiment The overall mean, median, and standard deviation of all experiments are denoted by grey shading (▭) * denotes significance from the legs experiment at the p<0 05 level

	AHGF		UB		Legs		mean		median		SD	
Participant	**uc**	**c**	**un**	**c**	**uc**	**c**	**uc**	**c**	**uc**	**c**	**uc**	**c**
c1	275	214	283	222	234	170	264	202	275	214	26	28
c2	155	110	201	155	156	108	171	125	156	110	26	27
c3	305	247	276	216	202	144	261	202	276	216	53	53
c4	389	324	361	292	317	250	356	289	361	292	36	37
c5	338	275	281	219	217	155	279	216	281	219	60	60
c6	400	321	349	275	364	290	371	295	364	290	26	24
mean	**310***	**248***	**292***	**230***	**248**	**186**						
median	**322**	**261**	**282**	**221**	**226**	**163**	*283*	*222*	*282*	*221*	*76*	*69*
SD	**90**	**80**	**58**	**49**	**77**	**69**						

Table 6.4. Mean gross sweat loss from all body mapping experiments uncorrected (uc) and corrected (c) for respiratory and metabolic mass loss at I1 and I2 Whole body surface area weighted sweat rate for all regions measured with pads for I1 and I2 *** denotes significance at the p<0 001 and ** at the p<0 01 level of significance between exercise intensities

	Gross sweat loss I1 (g)		Gross sweat loss I2 (g)		Gross sweat loss I1 ($g.m^{-2}.h^{-1}$)		Gross sweat loss I2 ($g.m^{-2}.h^{-1}$)		whole body SA weighted SR ($g.m^{-2}.h^{-1}$)	
									I1	I2
Participant	**uc**	**c**	**uc**	**c**	**uc**	**c**	**uc**	**c**		
c1	239	173	359	285	191	133	381	294	118	165
c2	142	103	212	156	116	86	230	175	37	73
c3	274	217	342	260	222	161	368	257	76	148
c4	381	309	516	432	308	225	556	420	207	250
c5	219	152	395	312	173	118	416	323	97	117
c6	371	296	512	407	281	218	517	399	130	232
mean ± SD	***271 ± 107***	***208 ± 92***	***389 ± 112****	***309 ± 100****	***215 ± 78***	***157 ± 66***	***411 ± 114****	***311 ± 93****	**111 ± 58**	**164 ± 67****

6.3.4.1 Gross Sweat Loss and Predicted Maximal Oxygen Uptake

Mean *GSL* (all experiments) was plotted against predicted $VO_{2\ max}$ for all participants and a regression line fitted (Figure 6.1). Participant c2 appears to have a low *GSL* for $VO_{2\ max}$ however was not identified as an outlier during analysis

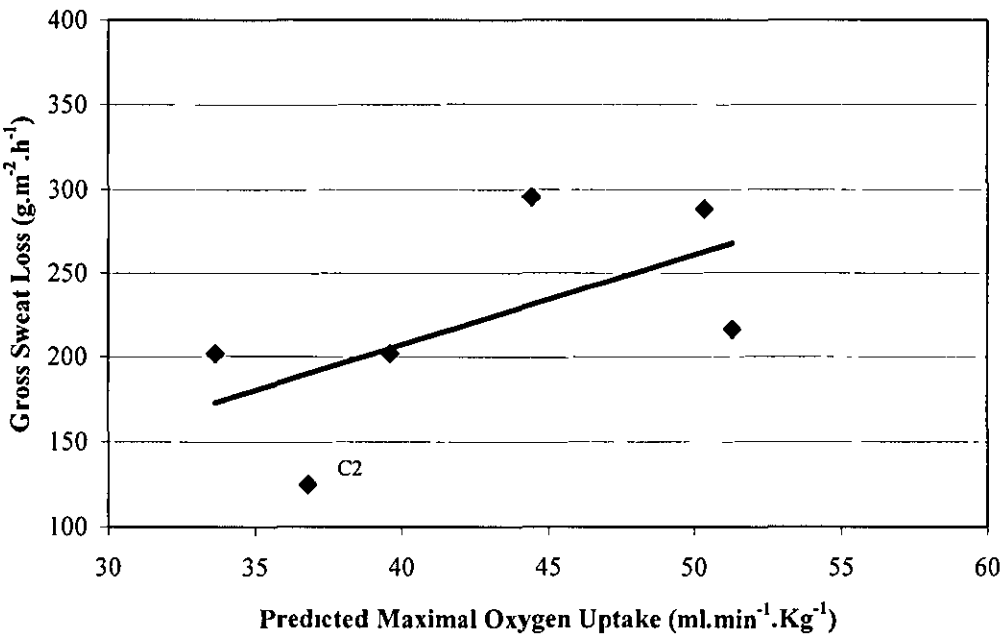


Figure 6.1. Gross sweat loss and predicted $VO_{2\ max}$ for untrained male participants

A non significant correlation (r = 0.612) was observed between and *GSL* $VO_{2\ max}$ in untrained males for the experimental conditions used The positive trend in the data suggests that a larger sample size may produce significance, as observed in male and female athletes.

6.3.4.2 Gross Sweat Loss and Metabolic Rate

Following secondary analysis of *GSL* in the discussion of Chapter 4 (4.4.2. Gross Sweat Loss), primary analysis of *GSL* and metabolic rate has been included in the results here. Mean (all experiments) *GSL* was plotted against metabolic rate (W m^{-2}) for I1 and I2 (Figure 6 2)

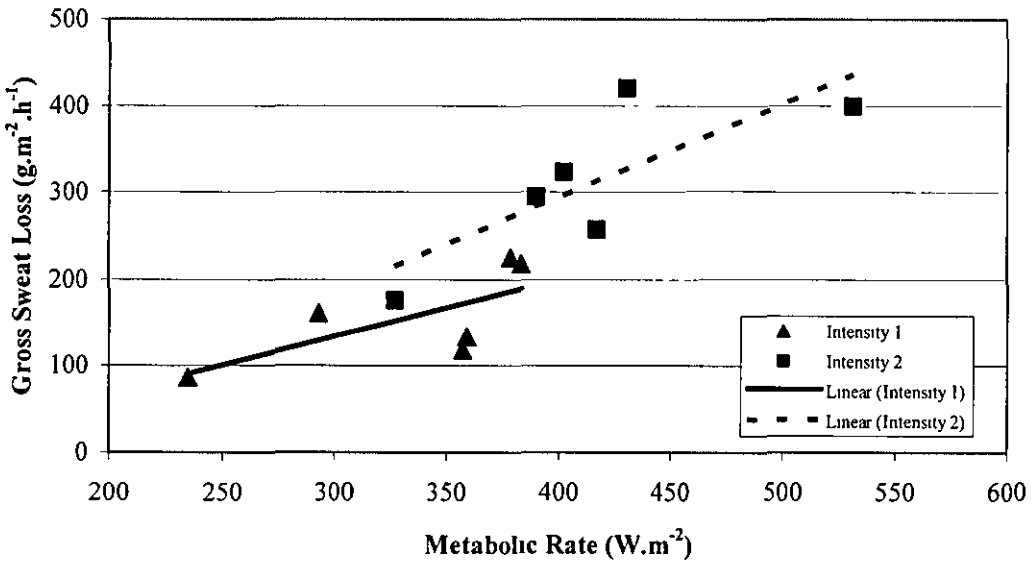


Figure 6.2. Mean Gross sweat loss and metabolic rate for untrained males at I1

A non significant, positive correlation was observed between *GSL* and metabolic rate at I1 ($r = 0.70$, $p = 0.123$) and I2 ($r = 0.79$, $p = 0.061$) This clearly indicates that when considering absolute rather than relative work rate, participants working at a higher metabolic rate exhibited a higher *GSL* proportional to their heat generation The steeper gradient present at I2 (1 08) compared to I1 (0 71) may suggest a decrease in mechanical efficiency, particularly since the untrained participants were required to walk at a greater gradient on the treadmill to increase work rate. There was however no significant difference between the gradients of the lines for I1 and I2, nor for the intercept with the Y axis.

6.3.5 Regional Sweat Rate

Regional sweat rate data was analysed for differences in corresponding right-left zones Paired t-tests were performed and Bonferroni correction was applied to adjust for multiple comparisons. Significant differences were present for the posterior lower leg ($p < 0.05$) and the lateral ankle ($p < 0.01$) at I2, with the left and right sides being higher for the respective regions Only the lateral ankle showed significance following Bonferroni correction ($p < 0.05$) Data was subsequently grouped for corresponding right-left zones at I1 and I2, with fingers and thumbs grouped separately despite no significant differences to maintain consistency with other chapters, with which the

current data will later be compared. Median right-left grouped data for all participants are illustrated for both exercise intensities in Figure 6 3 and Figure 6 4 respectively.

To explore regional variation of *SR* s within each exercise intensity, a repeated measures ANOVA was performed for I1 and I2. The reasoning behind this approach has been discussed in previous chapters (Chapter 4: 4.3.5. Regional Sweat Rates). Bonferroni correction was applied to adjust for multiple comparisons, however no significant differences (including $0.1 > p \geq 0.05$) were present following adjustment Comparisons of regional *SR* s may be observed in Table 6 7 and Table 6 10 for I1 and I2 respectively.

A number of patterns in regional *SR* s were observed in the majority of participants:

- Few significant right-left differences in corresponding zones
- Increase in gross and regional SR with exercise intensity
- Highest *SR* s over the body at I1 and I2 observed on the posterior torso, in particular on the medial (central) upper and mid regions.
- Lowest *SR* s in both exercise intensities observed on the extremities, particularly on the fingers, palms, and upper arms.
- Feet and ankles showed little increase in *SR* from I1 to I2
- Decrease in *SR* from medial to lateral across the torso
- Increase in SR from proximal to distal regions on the arms at both exercise intensities, although only significant at I2 (anterior and posterior uncorrected, $p < 0\ 05$)

In addition to the absolute sweat rates presented, individual data were normalised for the area weighted sweat rate of all regions in the individual and then the median of all individuals was taken. This allows easy identification of 'high' and 'low' sweat regions. Normalised sweat data for I1 and I2 are illustrated in Figure 6 5 and Figure 6 6 respectively.

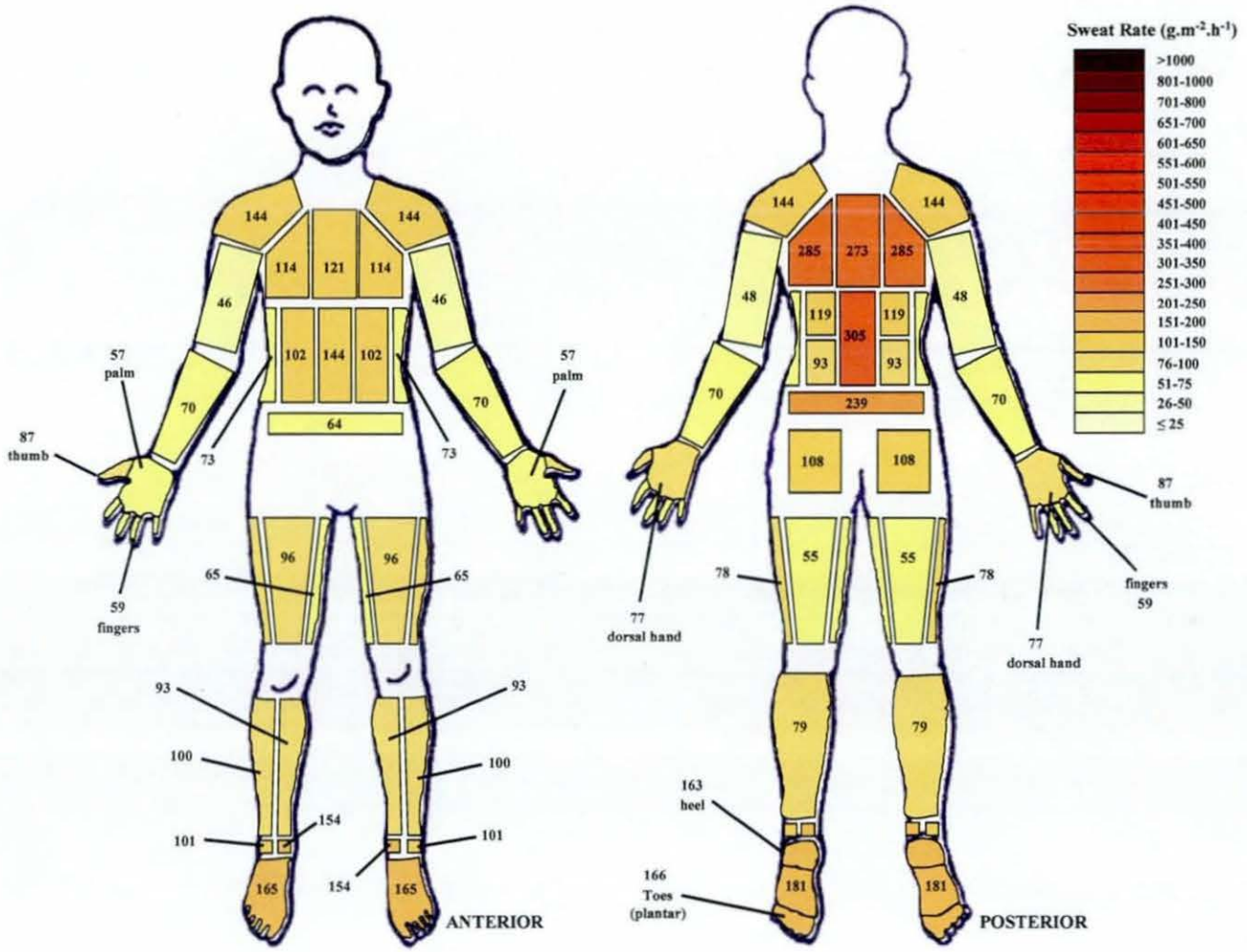


Figure 6.3. Median absolute sweat rate data ($g.m^{-2}.h^{-1}$) for I1.

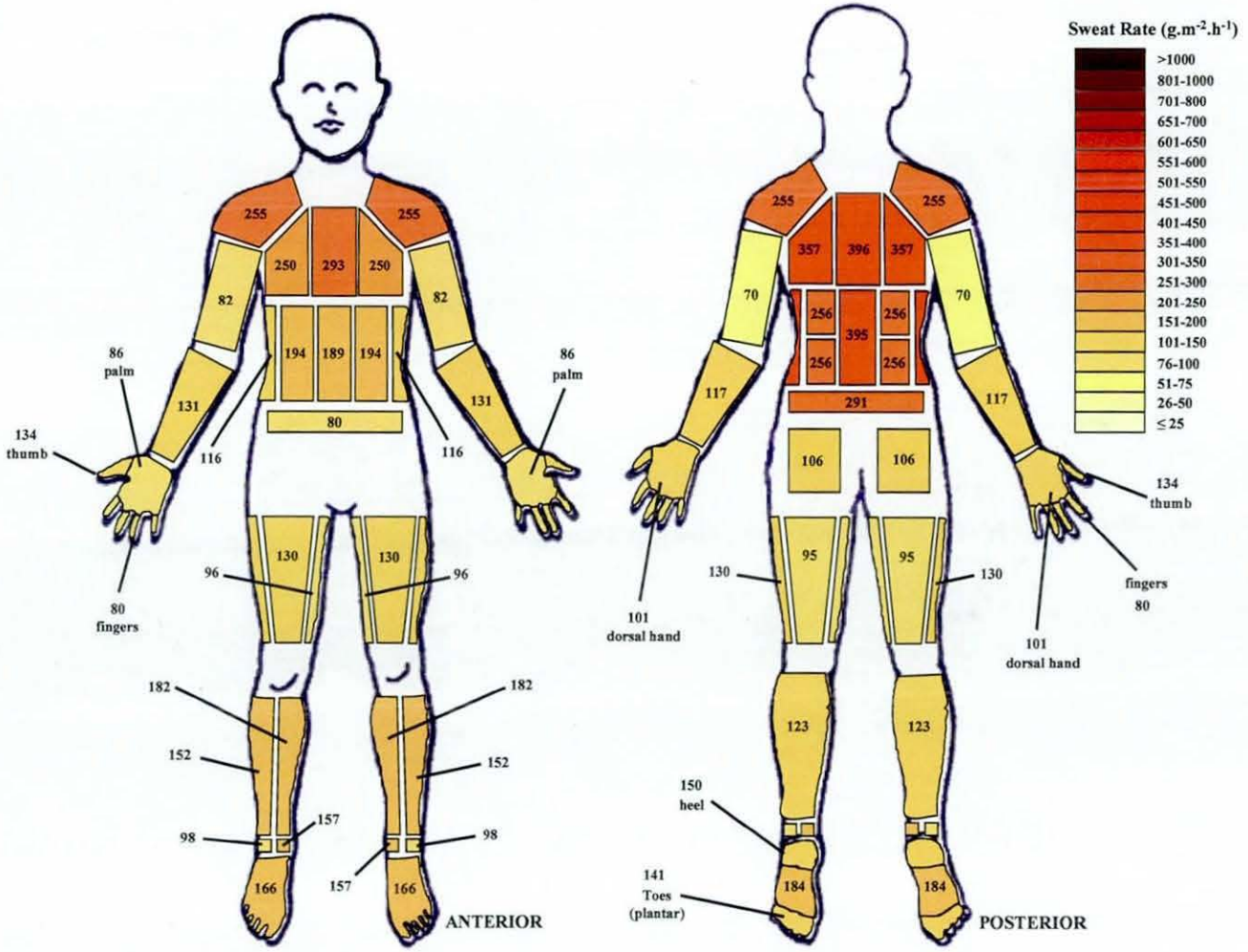


Figure 6.4. Median absolute sweat rate data ($g.m^{-2}.h^{-1}$) for I2.

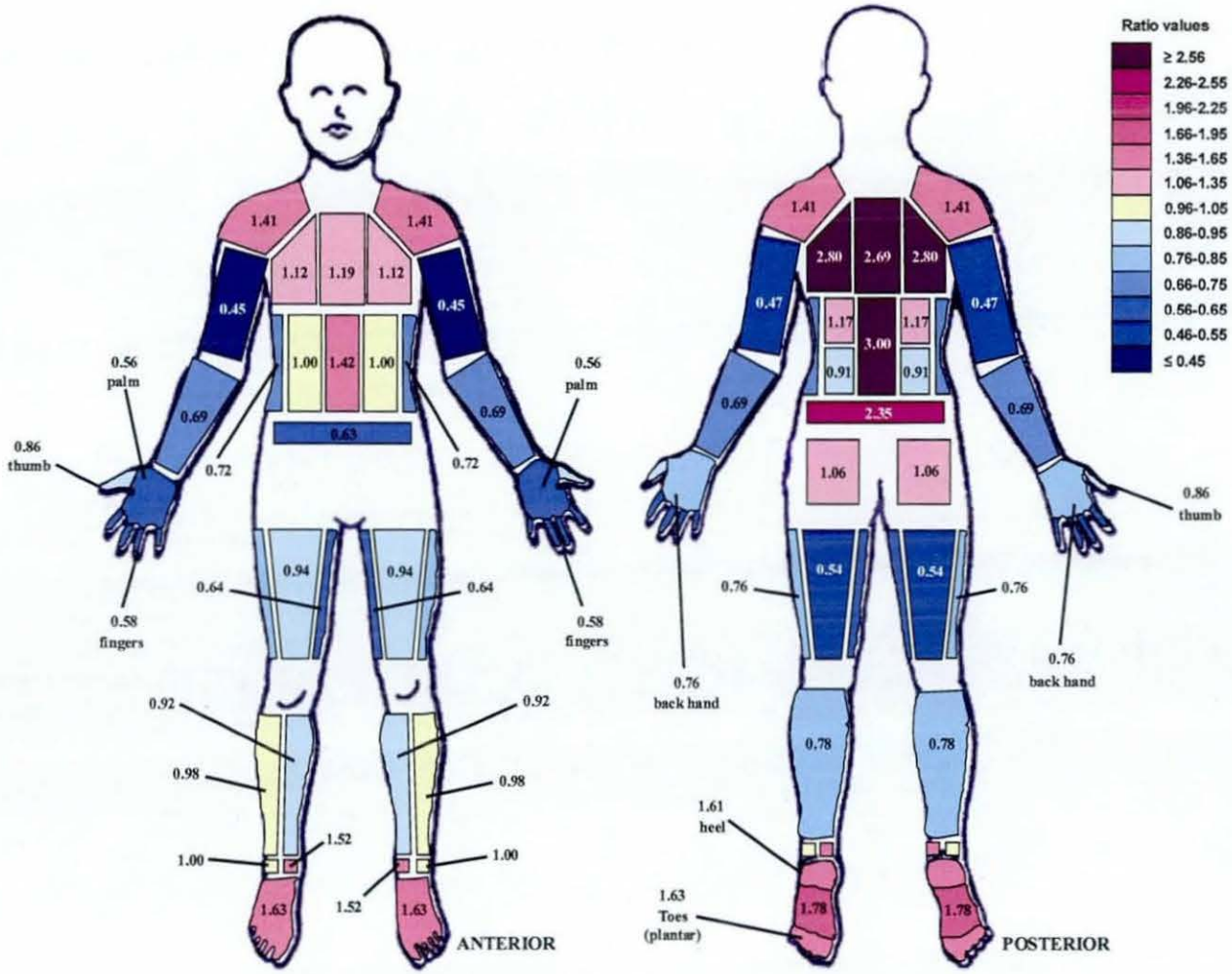


Figure 6.5. Normalised median sweat rate data for I1. A value of 1 indicates a sweat rate equal to the area weighted median sweat rate of all regions measured. Values above or below 1 indicate sweat rates higher or lower than the area weighted median sweat rate of all regions measured respectively.

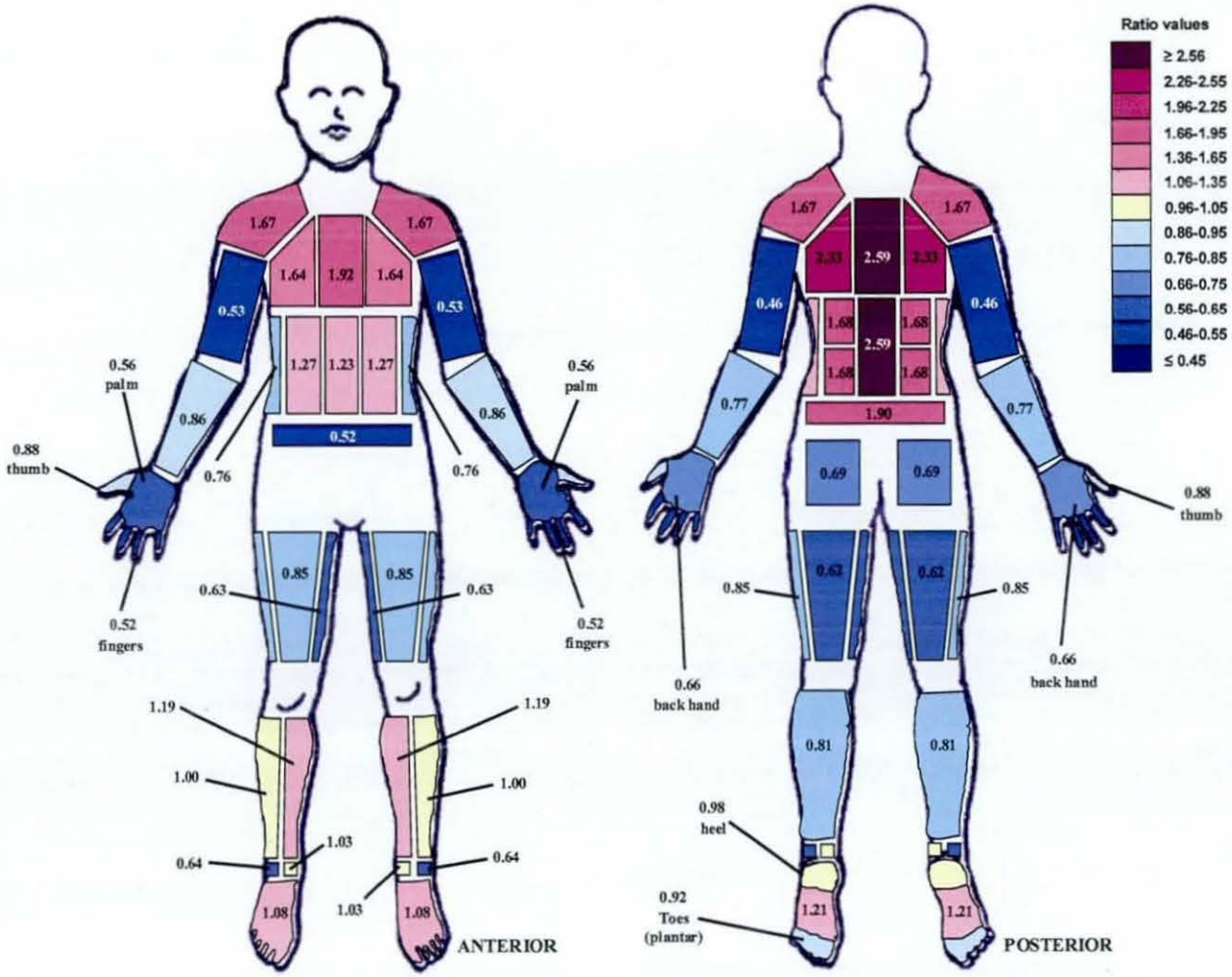


Figure 6.6. Normalised median sweat rate data for I2. A value of 1 indicates a sweat rate equal to the area weighted median sweat rate of all regions measured. Values above or below 1 indicate sweat rates higher or lower than the area weighted median sweat rate of all regions measured respectively.

The highest *SR* s over the body were observed on the posterior torso. Median (IQR) absolute values of 285 (152) g $m^{-2}.h^{-1}$, 273 (70) g m^{-2} h^{-1} and 305 (61) g m^{-2} h^{-1} were observed for the lateral upper, centre upper, and centre mid regions respectively at I1 These regions consistently showed the highest *SR* s at I2 with values of 357 (154) g m^{-2} h^{-1}, 396 (123) g m^{-2} h^{-1}, and 395 (241) g $m^{-2}.h^{-1}$ respectively Conversely, the lowest *SR* s were observed on the extremities, in particular the upper arms (anterior and posterior), fingers, and palms. Median (IQR) values of 46 (32) g m^{-2} h^{-1}, 48 (10) g m^{-2} h^{-1}, 57 (5) g m^{-2} h^{-1}, and 59 (7) g m^{-2} h^{-1} were observed at I1 for these regions respectively with a small increase to 82 (38) g $m^{-2}.h^{-1}$, 70 (26) g m^{-2} h^{-1}, 86 (34) g m^{-2} h^{-1}, and 80 (43) g $m^{-2}.h^{-1}$ at I2. These high and low sweat regions are clearly evident from the normalised sweat maps where a value of one is equal to the median *SA* weighted *SR* of all regions and values above or below one indicate *SRs* greater or less than the median *SA* weighted *SR* respectively (Figure 6 5 and Figure 6.6). Ratio values of 2 80, 2.69, and 3 00 were observed on the posterior lateral upper, centre upper and central mid regions at I1 and 2.33, 2.59, and 2 59 respectively at I2 In contrast, values of 0 46, 0.58, and 0 57 were observed on the anterior upper arm, fingers, and palms at I1, and 0.53, 0.52, and 0 56 respectively at I2.

A proximal to distal increase in sweat rate on the arms was present at both intensities yet only significant at I2 (anterior and posterior; $p < 0\ 05$) A medial to lateral decrease in *SR* across the torso was present at both exercise intensities but only significant on the posterior (pos mid lower vs centre pos mid, $p < 0\ 01$, pos mid lower vs centre pos mid, $p < 0\ 01$). The decrease on the torso from the posterior central mid to the posterior mid upper, posterior mid lower, and sides showed a median decrease (IQR) of 166 (84) g m^{-2} h^{-1}, 185 (113) g m^{-2} h^{-1}, and 246 (73) g m^{-2} h^{-1} respectively for I1 The decrease across the torso was not exacerbated by exercise intensity, with a decrease of 136 (48) g m^{-2} h^{-1}, 123 (18) g m^{-2} h^{-1}, and 235 (171) g m^{-2} h^{-1} at I2 between the respective regions.

A comparison of *SR* s between exercise intensities within each region was performed on all absolute and normalised data using a series of paired t-tests Table 6.5 provides the intensity comparison both uncorrected and corrected for multiple comparisons, in addition to descriptive statistics for all absolute regional sweat data

Table 6 5. Descriptive statistics for all regions sampled at I1 and I2 in untrained males A comparison of regional sweat rates between exercise intensities for both absolute and normalised data, corrected and uncorrected for multiple comparisons A decrease in median sweat rate between intensities is indicated by grey shading ([illegible]) No differences were significant after Bonferroni correction

	Absolute sweat data (g m^{-2} h^{-1})										Significance level of intensity comparison	
	I1					I2						
	min	max	median	mean	SD	min	max	median	mean	SD	Absolute data	Normalised ratio data
shoulders	0	393	144	164	132	16	716	255	295	230	*	-
lat upper chest	0	229	114	118	81	28	422	250	235	147	*	-
centre ant upper	0	355	121	141	136	33	484	293	280	172	*	-
lat mid chest	0	245	102	110	79	67	425	194	208	129	-	-
centre ant mid	9	446	144	180	151	34	506	189	220	171	*	-
sides	0	104	73	63	38	27	181	116	111	52	*	-
ant lower	0	254	64	100	102	10	258	80	108	91	-	-
lat pos upper	6	378	285	238	139	97	654	357	386	189	*	-
centre pos upper	7	409	273	240	133	65	604	396	350	182	*	-
lat pos M-U	0	249	119	121	79	51	351	256	215	127	-	-
lat pos M-L	0	249	92	113	88	54	361	256	216	121	*	-
centre pos mid	50	395	305	277	120	173	521	395	365	148	-	-
pos lower	24	454	239	254	157	89	570	291	310	176	-	-
ant upper leg	64	175	96	102	42	49	315	130	174	111	-	-
med upper leg	47	140	65	75	33	27	194	96	109	59	-	-
pos upper leg	44	119	55	70	31	40	275	95	115	83	-	-
lat upper leg	50	163	78	88	42	49	316	130	160	97	-	-
ant lat lower leg	58	261	100	126	76	67	356	152	190	124	-	-
ant med lower leg	77	240	93	124	64	61	405	182	222	139	-	-
pos lower leg	70	197	79	99	49	64	276	123	153	85	-	-
ant upper arm	0	54	46	33	24	13	95	82	71	30	**	*
pos upper arm	0	72	48	36	30	8	109	70	68	34	*	-
ant lower arm	3	112	70	61	48	20	185	131	119	58	*	-
pos lower arm	0	105	70	57	46	20	169	117	108	55	**	-
thumbs	52	114	87	84	20	54	164	134	119	46	-	-
fingers	39	73	59	58	11	38	480	80	141	168	-	-
palms	33	79	57	57	15	38	105	86	77	26	*	-
dorsal hand	27	117	77	72	32	38	174	101	109	51	*	-
gluts	21	146	108	97	47	82	216	106	125	52	-	-
sole	100	204	181	163	41	98	210	184	169	44	-	-
dorsal foot	67	1529	165	369	570	62	187	166	150	48	-	-
toes	86	179	166	150	38	91	153	141	135	23	-	*
heel	97	179	164	153	30	131	186	150	153	21	-	-
med ankles	52	233	154	143	66	71	292	157	171	87	-	-
lat ankles	6	154	101	83	64	0	145	98	84	62	-	-

For conversion to other units divide by 600 to get mg cm^{-2} min^{-1}, or by 10,000 to get ml cm^{-2} h^{-1}
*P ≤ 0 05, **P ≤ 0 01, ***P ≤ 0 001,

Only fourteen of the thirty five regions showed a significant increase in absolute *SR* from I1 to I2, none of which were significant following Bonferroni correction The regions showing a significant increase in *SR* with exercise intensity were concentrated on the torso and arms. There was little change in distribution of sweat over the body between I1 and I2 Only the anterior upper arm ($p < 0\ 05$) and toes ($p < 0\ 05$) showed a significant change in normalised values, with the former increasing and the latter decreasing with exercise intensity. These differences were not present following Bonferroni correction.

Table 6.6. Significance levels of comparison of absolute sweat rates for all regions at 11 uncorrected for multiple comparisons No significant differences were present following Bonferroni correction

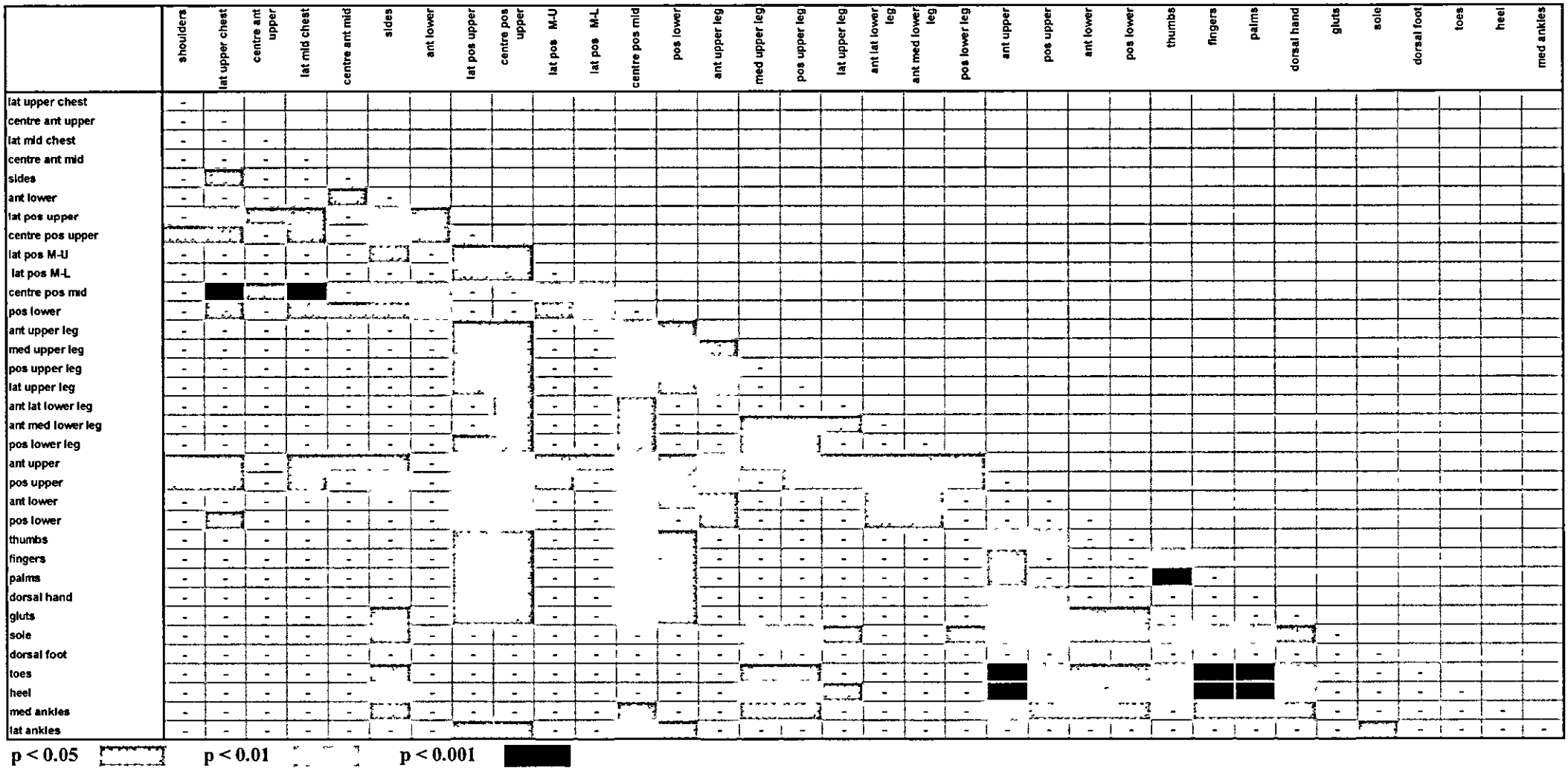
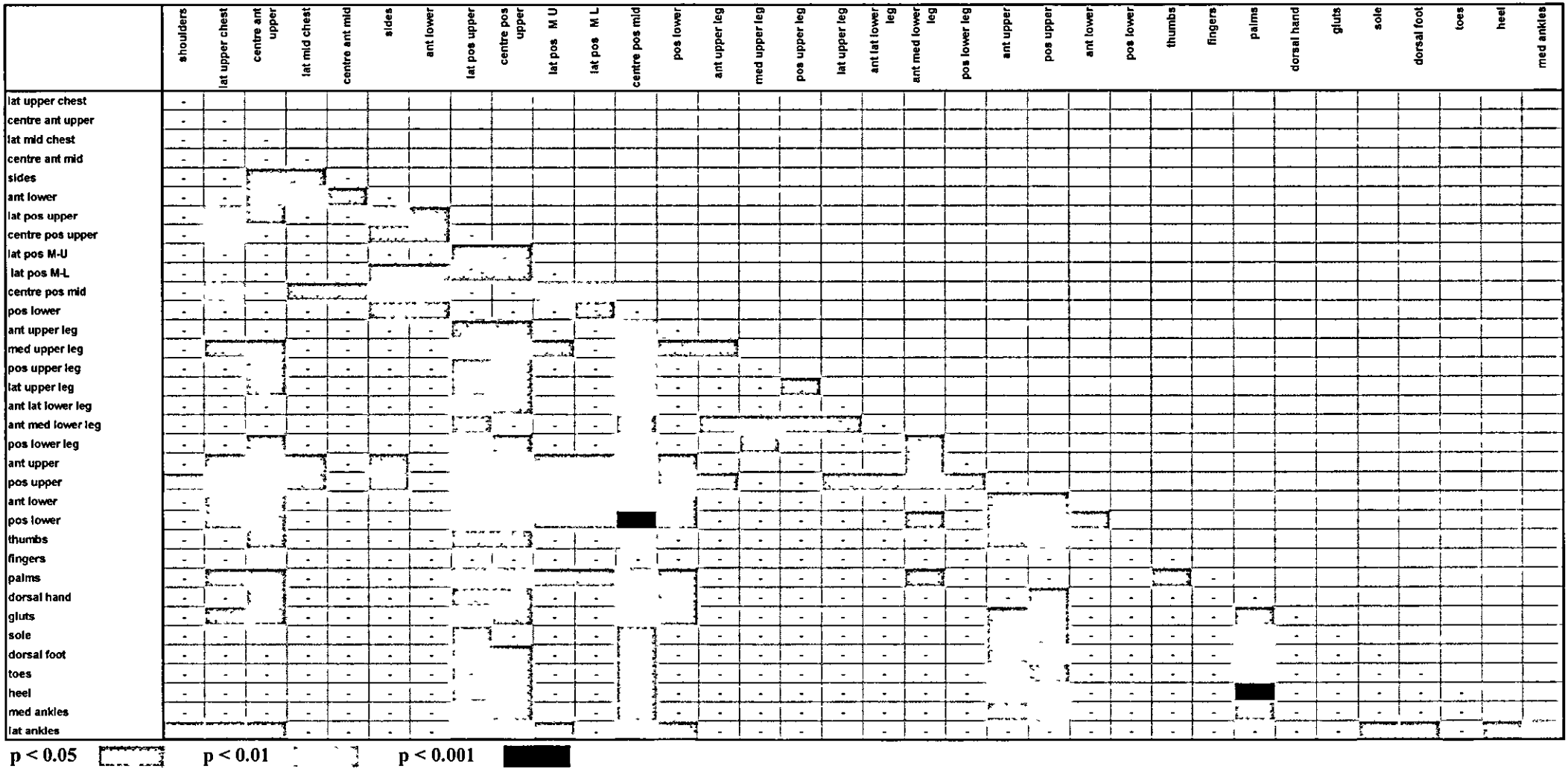


Table 6.7. Significance levels of comparison of absolute sweat rates for all regions at I2 uncorrected for multiple comparisons No significant differences were present following Bonferroni correction



6.3.6 Regional Skin Temperature

A one-way repeated measures ANOVA and pairwise comparisons were performed on all regional T_{sk} data for all separate measurement periods. Significance was present between most medial to lateral regions but was only present in seven out of 21 right-left regions (BL: posterior upper leg $p < 0.01$, pre I1 pads posterior lower arm $p < 0.05$, post I1 pads: anterior upper arm $p < 0.05$; Pre I2 pads: anterior lower arm $p < 0.05$, post I2 pads: anterior lower arm $p < 0.05$, hands $p < 0.05$). Only the *BL* posterior upper leg showed a significant right-left difference in T_{sk} following Bonferroni correction ($p < 0.05$). As with the athlete T_{sk} data in Chapters 4 and 5, data were grouped for corresponding right-left regions for analysis.

Grouped T_{sk} data at all measurement periods are presented in Table 6.8. Differences between measurement periods were analysed using paired t-tests and corrected for multiple comparisons. Data are presented both with and without Bonferroni correction. T_{sk} decreased significantly at five out of nine regions on the torso and at two out of ten on the arms, hand, and feet from *BL* to pre I1 pad application. Only the decrease at the anterior upper arms remained significant following Bonferroni correction. The heels and sole were the only regions to show a significant increase in T_{sk} from *BL* to the pre I1 measurement. This reflects the low *BL* T_{sk} in these regions since they displayed the lowest temperatures over the body with values of 26.1°C and 27.3°C on the heels and soles respectively. The torso appeared most affected by pad application at both exercise intensities. A significant increase in T_{sk} was observed at all nine regions, followed by a significant decrease in five of those regions after removal of the pads. No significant decrease in T_{sk} was present following I1 pad application following Bonferroni correction. No significant increase in T_{sk} occurred on the legs following I1 pad application however four out of six regions increased significantly following I2 pad application, none of which were significant following Bonferroni correction. Similarly the arms and feet showed little change following I1 pad application, however 6 out of 10 regions increased significantly from pre I2 to post I2 measurement periods, with only the anterior upper arm showing significance after Bonferroni correction. The feet and ankles showed no significant change between measurement periods during exercise.

Table 6 8. Regional skin temperature of male untrained body mapping participants at 5 measurement periods baseline (BL), pre I1 pad application (Pre I1), post I1 pad application (Post I1), pre I2 pad application (Pre I2), and post I2 pad application (Post I2) Significant changes within regions from the previous measurement period are indicated by the symbols listed below the table A significant decrease is indicated by grey shading (■)

		Skin Temperature (°C)				
Region		**BL**	**Pre I1**	**Post I1**	**Pre I2**	**Post I2**
UB	anterior medial upper	33 1	31 5	32 4**$	31 9	33 1*
	anterior lateral upper	32 8	30 6*	31 7**#	31 0	32 4**$
	anterior medial lower	31 5	29 7	31 0**#	29 6*	31 3**#
	anterior lateral lower	32 3	30 5*	31 9***##	30 3*	31 8**#
	posterior medial upper	33 3	31 5*	32 8**#	32 2	34 0*
	posterior lateral upper	32 8	30 8*	32 4**#	31 4*	33 5**#
	posterior medial lower	32 5	31 7	33 1**$	32 6	34 2**#
	posterior lateral lower	31 4	30 1	31 6**#	30 8*	32 6**#
	sides	31 9	30 4*	31 5**#	30 6*	32 0**#
Legs	anterior upper	31 0	31 5	32 5	31 0	33 6
	medial upper	31 1	32 1	33 1	31 1	34 2*
	posterior upper	31 3	33 0	33 7	31 3*	35 0**$
	lateral upper	31 8	32 4	33 3	31 8	34 5
	anterior lower	31 1	32 1	33 1	31 1	34 3*
	posterior lower	31 2	32 6	33 4	31 2	34 7*$
AHF	anterior upper	32 4	30.8**#	32 0*	31 2*	32 8**#
	posterior upper	31 3	31 5	32 3	32 1	33 6*
	anterior lower	31 7	30 1*	31 5**#	30 8	32 7*
	posterior lower	31 8	30 7	31 6	31 8	33 3
	palms	29 9	30 9	31 5	32 4	33 7*
	hands	29 3	29 6	30 4	31 1	32 3*
	heels	26 1	32 1**#	32 4	32 6	33 1*
	soles	27 3	33 0**#	33 2	33 4	33 7
	dorsal foot	31 5	33 2	33 5	33 6	34 5
	ankles (anterior)	31 9	31 8	32 4	32 4	33 4

No correction *P < 0 05, **P < 0 01, ***P < 0 001,
Bonferroni correction # P < 0 05, ## P < 0 05, ### P < 0 001, $ 0 1 > P ≥ 0 05

Regional T_{sk} responded similarly within body segments during sweat mapping Data were grouped into body segments to provide an overview of T_{sk} responses during testing Figure 6 7 demonstrates the fluctuation in T_{sk} with pad application and the rise in T_{sk} with exercise intensity Notably, the posterior lower leg showed a decrease from 33.4 ± 2.4°C to 31 2 ± 1 3°C from post I1 to pre I2, followed by an increase to 34.7 2 0°C at post I2. Only the latter change in T_{sk} was significant ($p < 0.05$), reflecting the large variation in the data. Figure 6 7 highlights the low *BL* T_{sk} observed on the feet and hands, however only the former showed a significant increase ($p < 0.01$) Little

change was observed on the feet throughout the remainder of the experiment, only showing a significant increase from pre to post I2 ($p < 0.05$, uncorrected). The hands showed a gradual rise in T_{sk} throughout the experiment, with only the increase from pre to post I2 pad application being significant ($p < 0.05$, uncorrected).

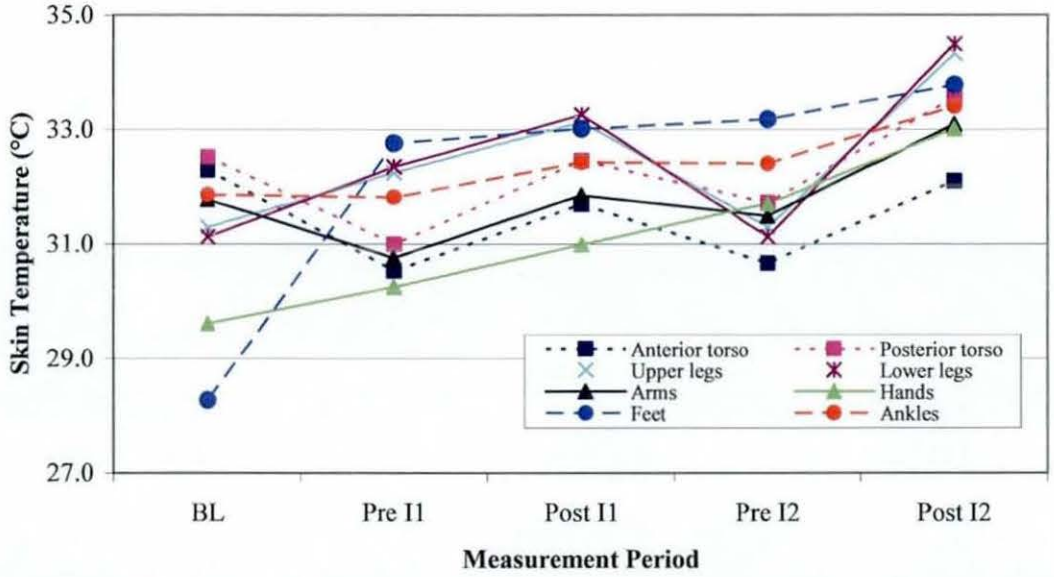


Figure 6.7. Regional skin temperature of untrained male body mapping participants at 5 measurement periods: baseline (BL), pre I1 pad application (Pre I1), post I1 pad application (Post I1), pre I2 pad application (Pre I2), and post I2 pad application (Post I2).

A Pearson's r correlation was performed between Regional T_{sk} and regional SR for each participant separately. Within participant analysis was performed due to confounding factors causing variation in between participants (described in Chapter 4: 4.3.6. Regional Skin Temperature). The regional SR at each intensity was compared with both pre and post pad application T_{sk} data. No correlation was present between regional SR and regional T_{sk} at I1 (pre pads: $r < 0.39$; post pads: $r < 0.38$) or I2 (pre pads: $r < 0.47$; post pads: $r < 0.48$) with exception to three participants showing weak, significant correlations (I2 pre I2 pads: c2 $r = 0.47$, $p = 0.017$; c5 $r = 0.46$, $p = 0.022$. I2 post I2 pads: c5 $r = 0.41$, $p = 0.041$).

6.4 Male Athlete- Untrained Comparison

A comparison of the male body mapping data discussed in Chapter 4 and the healthy male control data presented in the current chapter was performed.

6.4.1 Participant Characteristics

A summary of mean participant characteristics for trained and untrained males are presented in Table 6 9. Untrained male participants showed no significant differences in body characteristics from the male athletes, with exception to a significantly lower VO_2 max ($p < 0\ 05$) Surprisingly, there was no significant difference in body fat (%) between groups.

Table 6 9 A summary of mean participant characteristics of male athletes and untrained males * denotes significance from untrained males at the $p < 0\ 05$ level, and *** at the $p < 0\ 001$ level

Group	Age (yrs)	Height (cm)	Weight (kg)	Surface area (m^2)	Body Fat (%)	Predicted $VO_{2\ max}$ ($ml\ kg^{-1}\ min^{-1}$)	Av Total gross sweat loss based on mass loss ($g\ m^{-2}.h^{-1}$)
athletes	23 ± 3	178 5 ± 4 1	73 8 ± 5 0	1 92 ± 0 1	10 9 ± 4 9	70 2 ± 13*	473 ± 103***
untrained	22 ± 3	181 4 ± 4 0	78 23 ± 12 4	1 97 ± 0 1	14 1 ± 4 9	42 7 ± 7 2	222 ± 64

6.4.2 Gross Sweat Loss

An independent samples t-test was conducted to compare total *GSL* between groups Male athletes showed a significantly higher GSL at I1 and I2 ($p < 0\ 001$) and over the whole test period ($p < 0\ 001$).

6.4.2.1 Gross Sweat loss and Maximal Oxygen Uptake

GSL (mean of all body mapping experiments) was plotted against $VO_{2\ max}$ for all male athletes and untrained participants (Figure 6 8)

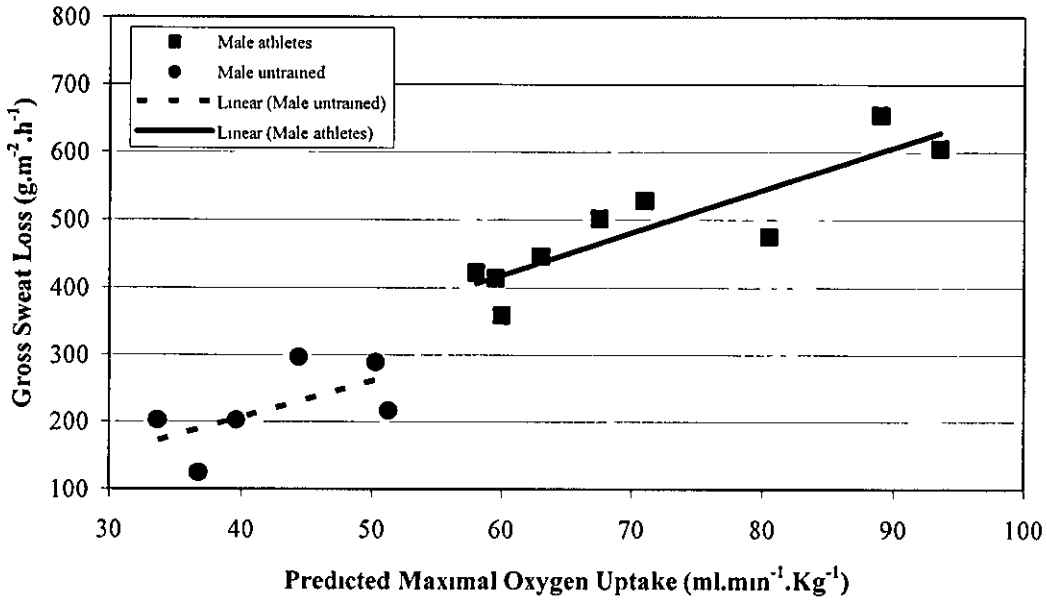


Figure 6.8. Gross sweat loss and predicted $VO_{2\,max}$ for all male athletes and untrained participants

A similar trend was present within both groups with *GSL* being higher in those with a higher VO_{2max}. A significant positive correlation was present for male athletes ($r = 0.88$, $p < 0.001$) but not untrained males ($r = 0.61$, $p = 0.20$), probably owing to the small sample size. No significant difference was present between the gradients of the regression lines between groups or the intercept with the Y axis When data from both groups are combined, a significant positive correlation was present between *GSL* and $VO_{2\,max}$ ($r = 0.94$, $p < 0.001$), with $\dot{V}O_{2\,max}$ accounting for 88% of variation in *GSL*.

6.4.2.2 Gross Sweat Loss and Metabolic Rate

Mean *GSL* of all sweat mapping experiments ($g.m^{-2}\,h^{-1}$) over I1 and I2 were plotted against metabolic rate ($W\,m^{-2}$) for each intensity for all male athletes and untrained males (Figure 6 9 and Figure 6 10) Male athletes had a significantly higher metabolic rate ($W\,m^{-2}$) than untrained males at both exercise intensities ($p < 0.01$) Correlational analysis between *GSL* and metabolic rate ($W.m^{-2}$) showed a positive correlation in both groups at I1 and I2, but only the athletes showed a significant relationship (athletes, I1 $r = 0.89$, $p < 0.001$, I2 $r = 0.77$, $p < 0.01$; untrained, I1 $r = 0.70$, I2 $r = 0.79$)

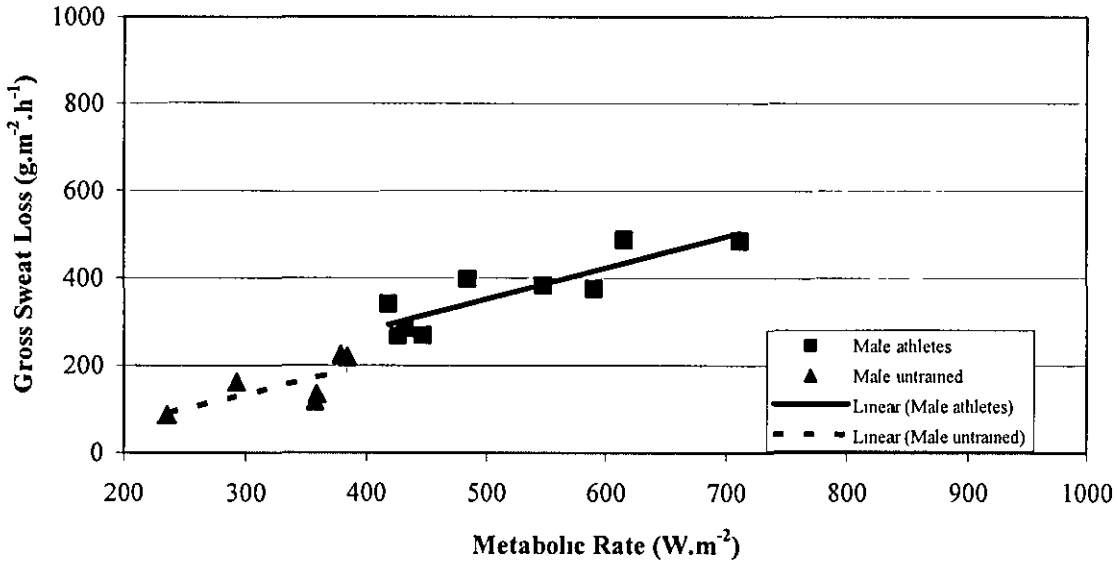


Figure 6.9. Gross sweat loss and metabolic rate of male athletes and untrained males at I1

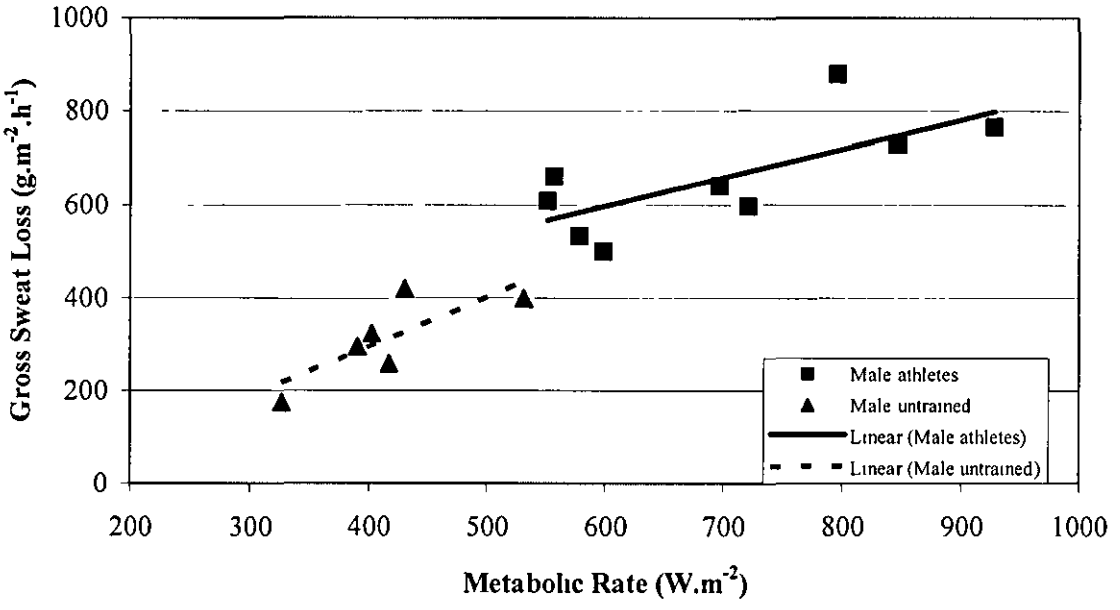


Figure 6.10. Gross sweat loss and metabolic rate of male athletes and untrained males at I2

No significant difference was present in the gradient of the regression lines or the intercepts between athletes and untrained males at I1 or I2. This indicates a similar sensitivity, producing the same increase in *SR* between participants per unit increase in metabolic rate. No significant differences were present between trained and untrained males for anthropometric and body composition measurements, therefore a similar

graph was produced when absolute *GSL* (g h^{-1}) was plotted against absolute metabolic rate (W), in addition to similar r values (athletes I1, r = 0 88, p < 0 01, I2 r = 0 78, p < 0 01; untrained I1, r = 0.84, p < 0 05, I2 r =0.88, p < 0 05). Graphs showing absolute *GSL* and absolute work rate are therefore not presented.

6.4.2.3 Gross Sweat Loss and Core Temperature

Mean *GSL* (all experiments) over the whole test period was plotted against mean T_{core} from I1 and I2 for all male athletes and untrained male participants (Figure 6.11).

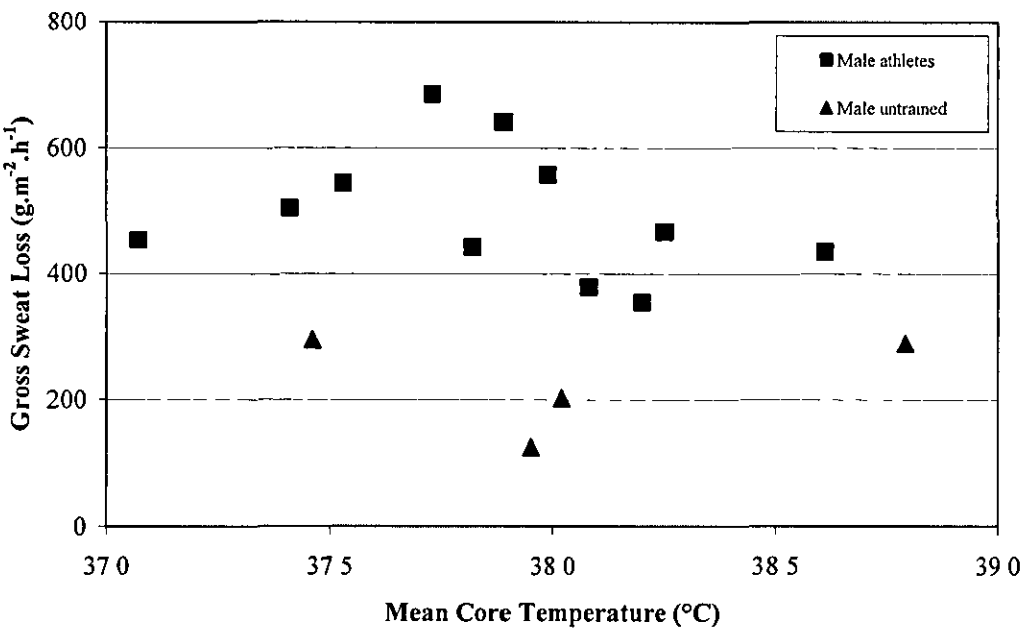


Figure 6.11. Mean gross sweat loss and mean core temperature of athletes and untrained males

Both groups displayed no correlation between mean GSL and mean T_{core}. As expected, T_{core} increased significantly during I1 and I2 in both male athletes (p < 0 001) and untrained participants (p < 0.05). The untrained males had a consistently higher T_{core} throughout the experiment, with values of 37 4°C, 37.9°C, and 38.2°C at BL, I1 and I2 respectively, compared to 36 9°C, 37.7°C, and 38.0°C in the male athletes None of these values were significantly different between groups at BL, I1 or I2

6.4.3 Regional Sweat Rate

Distribution of regional *SR* s between male athletes and untrained males was conducted using both area weighted data for all participants in addition to absolute regional sweat data As with the male-female athlete comparison in Chapter 5, the design was treated as repeated measures to allow a repeated measures ANOVA to be performed with sex, region, and sex-region interaction as factors Bonferroni correction was applied to adjust for multiple comparisons, with data presented both corrected and uncorrected (Table 6.10)

A significant main effect of region was present at I1 and I2 in both the absolute and ratio data ($p < 0.001$), indicating significant variation between groups in *SR* over the body A significant main effect of group ($p < 0.001$) was present in the absolute data, reflecting the significantly higher *GSL* in male athletes ($p < 0.001$) A significant group-region interaction was apparent in both absolute ($p < 0.001$) and ratio data ($p < 0.05$) at I1 and I2, indicating that some regions have higher *SR* s in male athletes and others in untrained male participants. Post hoc comparisons were performed to identify differences in distribution, with and without Bonforroni correction (Table 6 10). A small number of regions became significantly different between groups at I2 (anterior lower torso, top foot, toes, and lateral ankle), whilst only the fingers were significantly different at I1 (uncorrected, $p < 0.01$) but not I2, although neither are significant following Bonferroni correction The ratio data indicates little difference in the distribution of sweat over the body between male athletes and untrained males A small number of regions were significantly different in both exercise intensities, predominantly on the extremities, however no regions were significantly different between groups following Bonferroni correction, with only the sides showing a p value less than 0.1.

Table 6.10. Significance level of male athlete-untrained comparison of absolute and ratio regional sweat data Significantly higher values in untrained males compared to male athletes are indicated by grey shading (not [illegible])

	Significance level of male athlete-untrained comparison			
	Intensity 1		Intensity 2	
	Absolute data ($g\ m^{-2}\ h^{-1}$)	Normalised ratio data	Absolute data ($g\ m^{-2}\ h^{-1}$)	Normalised ratio data
shoulders	*	-	**	-
lat upper chest	**	-	**	-
med upper chest	*	-	**	-
lat mid chest	***#	-	**	-
med mid chest	*	-	***#	-
sides	**$	*	***##	**$
ant lower	-	-	**$	-
lat upper back	**$	-	***#	-
med upper back	***#	-	***##	*
lat mid upper back	***#	-	***##	-
lat mid lower back	**$	-	***#	-
med mid back	***##	-	***##	-
pos lower back	*	-	**	-
ant upper leg	**	-	*	-
med upper leg	*	-	*	-
pos upper leg	***#	-	**	-
lat upper leg	***#	-	*	-
ant lat lower leg	*	-	*	-
ant med lower leg	**	-	*	-
pos lower leg	**	-	*	-
ant upper arm	**	*	***#	*
pos upper arm	*	-	**	*
ant lower arm	**	*	***##	*
pos lower arm	*	*	***#	**
thumbs	**	-	**$	-
fingers	*	-	-	-
palms	-	-	-	*
back hand	*	-	**$	-
buttocks	**$	-	***#	-
sole	-	-	-	-
top foot	-	-	*	-
toes	-	*	*	*
heel	-	-	-	*
med ankle	**	-	*	-
lat ankle	-	-	**	-

For conversion to other units divide by 600 to get mg cm-2 min-1, or by 10,000 to get ml cm-2 h-1

No correction *P ≤ 0 05, **P ≤ 0 01, ***P ≤ 0 001,

Bonferroni correction # P ≤ 0 05, ## P ≤ 0 01, ### P ≤ 0 001, $ 0 1 > P ≥ 0 05

6.4.4 Regional Skin Temperature

A comparison of regional T_{sk} between trained and untrained males was performed at each measurement period. A series of independent t-tests were conducted and adjusted for multiple comparisons using Bonferroni correction. Only a small number of significant differences were present between the two groups Untrained males had a significantly higher T_{sk} for the dorsal foot ($p < 0.05$) and ankles ($p < 0.05$) at *BL* and the anterior lower leg ($p < 0.05$) and posterior lower leg ($p < 0.05$) at post I2 pad application. The male athletes (trained) showed a significantly higher T_{sk} at the anterior lower arm at pre ($p < 0.05$) and post ($p < 0.05$) I1 pad application. No significant differences were present following Bonferroni correction.

6.5 Discussion

6.5.1 Core Temperature

Both male athletes and untrained males showed a characteristic rise in T_{core} expected with exercise and/or exposure to warm environmental conditions (Kenny *et al*, 2008) The physiological mechanisms behind the development of this hyperthermic response have been discussed in detail in Chapter 4 (4 4.1 Core Temperature) Interestingly, no significant differences were present in T_{core} between the two groups at any stage of the experiment, although the untrained participants consistently showed a slightly higher T_{core} than the athletes Since there were no significant differences in body characteristics between the two groups this may seem unsurprising The impact of morphological differences upon thermoregulation have been well recognised not only between sexes but within populations. In particular, body *SA* and body composition, more specifically fat free mass and body fat content, determine the heat production and heat exchange capacity of the body (Bar-Or *et al*, 1969; McArdle *et al*., 1984; Havenith, 1985) However, $\dot{V}O_{2\,max}$ was significantly higher in the male athletes ($p < 0.05$), causing their absolute work rate to be significantly higher than the untrained males ($p < 0.01$) Mean T_{core} over both I1 and I2 was subsequently plotted against mean metabolic rate (all experiments) over both exercise intensities (Figure 6 12) No correlation was observed

between T_{core} and metabolic rate for the male athletes (r =-0.19), untrained participants (r = 0.14), or when both groups were combined (r = 0 25) As previously discussed in Chapter 4 (4 4 1. Core Temperature), participants with a greater $VO_{2\ max}$ may display a similar T_{core} to those less fit whilst working at a higher VO_2 but equal percent $VO_{2\ max}$ This results from an acquired degree of acclimatisation from repeated bouts of high intensity exercise eliciting a high T_{core}.

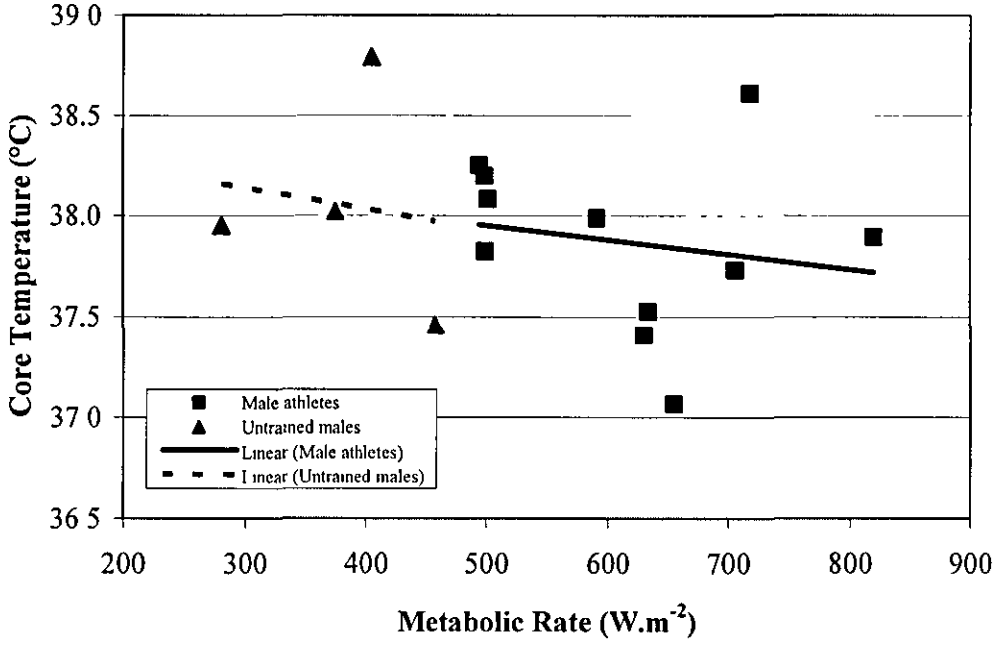


Figure 6.12. Mean core temperature and mean metabolic rate for male athletes and untrained male participants

6.5.2 Gross Sweat loss

Large variation in *GSL* was observed both within and between untrained male participants under the present experimental conditions. The mean absolute difference between sessions was 49 ± 30 g m^{-2} h^{-1}, with a range of 2 to 120 g m^{-2} h^{-1}. These values were lower and showed less variation than in the current male athlete participants, showing a mean absolute difference of 77 ± 60 g $m^{-2}.h^{-1}$ between experiments, ranging from 8 to 203 g $m^{-2}.h^{-1}$. A significant increase in GSL was present from I1 to I2 in untrained males ($p < 0\ 001$). Despite all experimental sessions being of identical format, the legs experiment had a significantly lower GSL than the other body mapping

experiments ($p < 0.05$) Each participant performed their sessions at the same time of day to prevent circadian effects, however different participants were tested at different times, and therefore inter individual variations in circadian variation was not controlled.

GSL at I1,I2, and overall was significantly higher in the male athletes compared to the untrained males ($p < 0.001$), with overall mean GSL (all experiments) values of 483 ± 110 and 222 ± 69 $g\ m^{-2}\ h^{-1}$ respectively Athletes have commonly been reported to sweat more and to have a shorter onset time compared to untrained individuals (Nadel *et al*, 1974) This phenomenon of an increased thermoregulatory capacity results from a frequent elevation in T_{core} from high intensity exercise and/or high ambient temperatures in addition to the cardiovascular adjustments associated with training The resultant thermal adaptation produces a state of partial heat acclimatisation, which elicits a decrease in resting T_{core} (Shvartz *et al*, 1974) and maintenance of a lower T_{core} for a given work rate due to a more rapid and pronounced sweat response (Taylor and Cotter, 2006) The shift in the threshold for sweating and a change in gain of the $SR-T_{core}$ relation observed with training (Henane *et al.*, 1977), is supported in the present data when considering the significantly higher *GSL* and metabolic rate in male athletes compared to untrained males, yet no significant difference in T_{core} Similar results have been observed by other authors using relative rather than absolute work rates to compared trained and untrained individuals (Saltin and Hermansen, 1966; Greenleaf *et al*, 1972; Nadel *et al*, 1974), fitting extremely well with T_{core} relating to relative work rate ($\%VO_{2max}$), and *SR* relating to absolute work rate

6.5.3 Regional Sweat Rate

Despite significant differences in *GSL* ($p < 0\ 001$), little difference was observed in the distribution of sweat between male athletes and untrained males Upon analysis of the absolute data a high number of significant differences were apparent between groups, yet these simply reflect the difference in *GSL*. Since the regional sweat distribution in untrained males and male athletes was similar, a detailed discussion of regional *SR* in relation to regional sweat gland density, gland sensitivity, and output per gland will not

be repeated A detailed discussion on the literature may be referred to in Chapter 4 (4.4.3. Regional Sweat Rates)

The ability of athletes to produce a greater quantity of sweat with a shorter onset during exercise and/or in hot conditions, allows them to maintain a lower T_{core} compared to untrained individuals exercising at the same work rate (Nadel *et al.*, 1974) Although a degree of acclimatisation experienced by athletes is recognised (Taylor and Cotter, 2006), the question as to whether or not distribution of sweat is different in athletes compared to untrained individuals has not be adequately addressed. The current normalised data suggests that there is no significant difference in the distribution of sweat in male athletes compared to untrained males in the conditions used Both groups experienced the highest sweat rates on the posterior torso and the lowest on the extremities. The medial to lateral decrease in regional sweat rate over the torso, although apparent in both groups, was only significant on the posterior within the untrained male participants whilst significant on both the anterior and posterior in the male athletes Interestingly, the differences became exacerbated by exercise intensity within the athlete group yet the differences in medial and lateral sweat rate decreased within the untrained males The medial to lateral decrease across the torso has been observed by a number authors (Ogata, 1935, Kuno, 1956; Hertzman, 1957; Havenith *et al.*, 2008, Machado-Moreira *et al*, 2008a) but was absent in work by Cotter *et al* (1995) Notably none of these groups used sub elite or elite athletes as participants, supporting the presence of a similar regional sweat distribution in less fit and trained individuals. Hertzman (1957) observed a lateral decrease in *SR* across the torso however a more uniform regional *SR* developed with increasing heat stress A similar finding was present in the current data with no significant differences in medial and lateral regions of the anterior torso in the untrained males at I2.

Male athletes appear to have a greater ability to thermoregulate compared to untrained individuals, and evidence of a greater efficiency with greater peripheral relative *SR* s Females have been described as possessing a greater 'sweating efficiency' due to their ability to maintain a similar T_{core} to males whilst demonstrating a lower sweat rate (Avellini *et al.*, 1980a; 1980b; Frye and Kamon, 1981). In the present study, female athletes (Chapter 5) also showed a greater peripheral relative *SR* compared to male

athletes. This implies a better utilization of large *SAs* for heat loss, which posses a greater heat transfer coefficient when moving during exercise Such efficiency of sweating has been observed in a redistribution of sweat towards the limbs during acclimation to humid heat, shifting towards areas with most favourable evaporation (Hofler, 1968, Shvartz *et al*, 1979) The male athletes in the present study showed significantly higher relative *SR* s on the arms at both exercise intensities, suggesting possible evidence of a greater efficiency with an increase in cardiovascular fitness Since athletes are thought to possess a low level of heat acclimation, they may achieve some degree of redistribution in *SR* The absence of a redistribution towards the limbs has however been observed by some authors during heat acclimation (Weiner, 1945, Fox *et al*, 1964;).

6.5.4 Regional Skin Temperature

Regional T_{sk} was measured during the present study to evaluate local differences over the body, changes with exercise intensity and pad application, and to establish any relationship with regional *SR* As discussed in previous Chapters (Chapter 4: 4.4.4. and Chapter 5: 5.5.4. Regional Skin Temperature), there is a general consensus that eccrine sweat gland activity is largely controlled by a centrally-mediated drive which detects changes in T_{core}, and a smaller contribution ($1/10^{th}$) of the $\overline{T}_{sk}$, yet may be modified peripherally by local conditions (Nadel *et al*, 1971a; 1971c, Van Beaumont and Bullard, 1965; Ogawa and Asayama, 1986, Dipasquale *et al*, 2003) The presence of a correlation between regional *SR* and regional T_{sk} was therefore expected in the current data, given T_{core} and $\overline{T}_{SK}$ was identical for all regions However, no correlation was observed between the two variables at any measurement period ($r < 0\ 48$), as similarly observed in the male and female athletes in the present series of studies As discussed in Chapters 4 and 5, it is likely that the dynamic interplay between heat loss and heat gain form the surface of the skin during exercise produced no relationship between the two variables within such a narrow T_{sk} range (29 6-35 0°C). A similar conclusion was draw by Cotter *et al* (2005) who only explained 2 5% of regional sweat distribution by regional T_{sk}, however they observed a narrower range of local T_{sk} (35.8–36 6°C) This observation was during both steady state and transient sweating, with the dissociation of

the two variables being attributed to a narrow T_{sk} range (35 8-36 6°C). Furthermore, sweating at regions of skin overlying active muscles during exercise does not appear to modify sweat rate in those regions (Bothorel *et al*, 1991) The regional variation in T_{sk} and the exercise mode therefore do not provide an explanation for the regional variation in SR observed in untrained males under the experimental conditions used.

Regional T_{sk} decreased significantly from BL to pre I1 pad application in 5 out of 9 regions on the torso and 2 out of 4 regions on the arms. The heels and soles were the only regions in which T_{sk} increased significantly, reflecting the low BL values. Since participants were tested during the winter, they exhibited a low T_{sk} on their feet upon arrival at the laboratory. These low BL values and the significant increase during I1 indicate the need for an 'acclimation' period in the experimental condition prior to testing Fluctuations in T_{sk} were evident with pad application, in particular, all regions on the torso increased significantly following pad application at both exercise intensities (uncorrected for multiple comparisons). Interestingly, the anterior torso exhibited some of the lowest sweat rates over the body, suggesting that the absorbent material had little local effect of artificially increasing SR from an increase in local T_{sk}

6.5.5 Conclusions

Following whole body sweat mapping of untrained Caucasian males during steady state exercise in a moderate environment, and a comparison with data from Caucasian male athletes, the following conclusions were drawn

- Large inter and intra regional variation in gross sweat loss was observed in untrained males
- Male athletes had a significantly higher gross sweat loss than untrained males at the same relative work rate, resulting from a higher absolute work rate. However, no difference in sweat sensitivity (sweat increase per unit increase in work rate) was present between groups
- Male athletes had significantly higher absolute regional sweat rates than untrained males, however similarities in distribution were present

- Highest sweat rates were observed on the medial and lower posterior torso in athletes and untrained males, with values being greater on the posterior than anterior torso Lowest sweat rates were observed towards the extremities, in particular on the fingers, palms, and upper arms
- Most sweat rates increased significantly with exercise intensity in both groups, with exception to the feet.
- Male athletes showed a superior thermoregulatory ability compared to untrained males. No significant differences were present in T_{core} or T_{sk} yet the male athletes exercised at a significantly higher absolute work rate than untrained males. This fits extremely well with T_{core} relating to relative work rate and sweat rate relating to absolute work rate.
- Regional sweat rate could not be explained by regional skin temperature since no correlation was observed between the two variables

Chapter 7

Study 5: Body Sweat Mapping of Male Athletes following Acclimation to a Hot-Dry Environment

7 Chapter Summary

In the current chapter, sweat mapping of the upper body in male athletes has been explored following six consecutive days of acclimation to hot-dry heat Participants exercised intermittently for 60 minutes at a sub-maximal level during 90 minutes of exposure to 45°C and 20% *rh*. An increase in T_{core} 1.4°C above *BL* was to be achieved during each exposure On the seventh day, a post acclimation sweat test was performed on the upper body to compare the quantity and distribution of regional *SR* s with *BL* data in Chapter 4. The protocol of the sweat test was identical to the torso and arm sweat mapping conducted on male athletes (Chapter 4). A significant in *GSL* was observed between pre and post acclimation sweat tests ($p < 0\ 01$), however no change in regional distribution was present. Regional T_{sk} showed no significant difference between pre and post acclimation, and was not correlated with regional sweat rate

7.1 Introduction

Repeated exposure to hot conditions elicits a multitude of progressive adaptive responses to reduce the thermal strain placed upon the body Most notably, the circulatory, thermal and body fluid responses during heat acclimation produce a lower *HR*, higher *SR*, and lower T_{core} for a given workload (Havenith and Middendorp, 1986) These adaptations are considered to result from both central and peripheral modifications of the thermoregulatory system A downward shift in the sudomotor threshold with acclimation (central adaptation) coupled with morphological and functional adaptations at the sweat glands, produces a greater and more sustainable sweat capacity and an earlier sweat onset (Fox *et al*, 1964; Peter and Wyndham, 1966, Henane and Valatx, 1973; Inoue *et al*, 1999)

The adaptations in both gross and regional sweat loss with repeated heat exposure are well documented (Fox et al , 1967; Hofler, 1968, Candas *et al* , 1983), however, the latter has only been studied on a limited number of sites each covering only a small surface area. The consensus amongst studies is for an increase in both regional and *GSL* following acclimation, with a more uniform *SR* over the body surface (Höfler, 1968).

Controlled hyperthermia techniques provide a more complete adaptation to heat than other acclimatisation regimes, producing a rapid elevation in T_{core} which is clamped for the duration of exposure. The elevation in T_{core} is maintained during successive exposures through an increase in work load, causing the stimulus for adaptation to be greater than in self regulated or constant load function regimes. Since most adaptive responses are complete within the first seven days of heat exposure (Robinson *et al*, 1943; Henane and Valatx, 1973) and athletes are known to acclimate more rapidly than untrained individuals (Bean and Eichna, 1943, cited in Greenleaf *et al.*, 1972), six days of consecutive heat exposure were performed. Acclimation to hot-dry conditions has been observed to produce a more rapid adaptation due to limited hidromeiosis and so a hot-dry climate was selected for the present acclimation The current study will therefore investigate the quantity and distribution of sweat from the torso and arms of trained, unacclimated males following six consecutive days of 90 minute hot-dry heat exposure using a controlled hyperthermia technique

7.2 Methods

7.2.1 Participants

Six male athletes from the original sweat mapping experimentation (Chapter 4) provided informed consent to participate in the current study Participants m2, m4, m6, m7, and m9 had previously completed the body mapping experimentation, whilst m12 had only performed sweat mapping of the head, face and neck Consequently, participant m12 was required to perform a pre acclimation (*BL*) sweat test of the upper body (torso and arms) before commencing the acclimation regime

7.2.2 Methodology

For the definition of pre acclimation data, values obtained in chapter 4 were used. A post acclimation sweat test (body mapping) of the torso and arms was conducted following six consecutive days of heat acclimation during the summer The experimental set up and methodology for the sweat test is identical to that described in Chapter 2 (2 5 Generic Sweat Mapping Protocol) The methodology in the current chapter will therefore outline only the acclimation regime A pre test session had previously been completed by all participants in conjunction with body sweat mapping and did not need repeated The methods are additionally described in detail in Chapter 2 (2.3. Pre-Experimental Test Session)

7.2.2.1 Ethical Clearance and Safety

The laboratory methods undertaken in the current chapter have been approved by Loughborough University's ethical committee. Ethical clearance and safety precautions for both acclimation and the post acclimation sweat mapping are outlined in detail in Chapter 2 (sections 2 2 1 to 2 2.3). Since the acclimation protocol required a 1.4°C increase in T_{core} above BL, values approaching 39°C were anticipated To ensure the safety of all participants, the safety guidelines and withdrawal criteria described in Chapter 2 were strictly observed.

All participants were provided with a 'participant information sheet' (appendix A) informing them of the aims and procedure of the experiments. They were permitted to familiarise themselves with the climatic chamber and equipment before signing an 'informed consent' document (appendix A). A 'generic heath screen questionnaire' (appendix A) was completed by every participant to ensure they were still suitable to undertake the study since completing the body sweat mapping

7.2.2.2 Experimental Set Up

All experiments were conducted in a climatic chamber in the Human Thermal Environments Laboratory, Loughborough University For the acclimation procedure exercise was performed on a cycle ergometer (Monarch) with three 50cm diameter fans (JS Humidifiers plc, Littlehamption, UK) arranged in a vertical line 1 metre in front of

the bike (Figure 7.1). This enabled an equal distribution of wind over the height of the body, set at an air velocity of 1.0 $m.s^{-1}$. Regular calibration of air velocity was performed using a hot wire anemometer (model TSI Alnor 8455. TSI Instruments Ltd, High Wycombe, UK. Range 0.125-50 $m.s^{-1}$.) at the position of the cycle ergometer seat. Data output was recorded on a Eltek/Grant 10 bit, 1000 series squirrel data logger (Grant Instruments, Cambridge, England) at 30 second intervals.

Figure 7.1. Experimental set up for the heat acclimation testing.

7.2.2.3 Acclimation Protocol

On arrival at the thermal laboratory all participants were requested to attend the toilet if required before beginning the 90 minute acclimation procedure. Participants changed into their own shorts and were weighed on electronic scales (Mettler Toledo kcc150 , 150 kg. Mettler Toledo, Leicester. UK.) without socks and shoes to attain their pre-test weight. Water bottles were labelled and weighed on electronic scales to monitor fluid consumption before being placed inside a cool box in the chamber. Following careful instruction, each participant inserted a rectal thermistor (Grant Instruments, Cambridge, England) 10cm beyond the rectal sphincter for measurement of T_{core} during acclimation. Four skin thermisotors (Grant Instruments, Cambridge, England) were attached to the upper arm, chest, thigh and lower leg using medical tape, to allow the calculation of mean T_{sk}, as described by Ramanathan's weighting formula (Ramanathan, 1964). The skin and rectal thermistors were attached to an Eltek/Grant 10 bit, 1000 series squirrel

data logger (Grant Instruments, Cambridge, England) and bound together with wire to form one large cable for ease during testing Participants were fitted with a polar heart rate monitor and watch (Polar Electro Oy, Kempele, Finland) which recorded heart rate at 5 second intervals. Participants were asked to sit in the preparation room for 15 minutes whilst answering questions regarding thermal and comfort sensation. A resting heart rate was recorded before proceeding to the thermal chamber

Before commencing the acclimation regime adjustments were made to the cycle ergometer for the use of each participant and a level of resistance was established which could be maintained for the first exercise period Recordings of T_{core}, T_{sk}, T_a, rh, and heart rate at one minute intervals were started, in addition to manual readings taken every five minutes The acclimation regime was based on the Fox technique, and involved intermittent exercise in 45°C and 20% rh (hot-dry) to achieve a T_{core} 1.4°C above BL. Participants exercised sub-maximally for 20 minutes, followed by a 10 minute rest period, which was repeated for the duration of the 90 minute exposure Resistance was adjusted to achieve the desired increase in T_{core} or at the request of the participant If T_{core} approached 39°C participants ceased exercise and sat on the cycle ergometer to limit any further increase

Following each 90 minute exposure, all equipment was removed from the participant and they were re-weighed wearing only their shorts. Only when T_{core} and heart rate had decreased towards the pre-exposure value were participants advised they could leave the laboratory.

7.3 Results: Acclimation

7.3.1 Participants

The physical characteristics of participants involved in the acclimation experiments are provided in Table 7.1 Heart rate and work rate were calculated as the mean (±SD) over all exercise bouts during a single exposure. The same male athletes were used in acclimation as in the body sweat mapping in Chapter 4 Inclusion criteria for participants may therefore be referred to in Chapter 4 (4.2 1. Participants)

Table 7 1. Participant characteristics for the acclimation procedure and pre-post acclimation sweat mapping

Participant no.	Age (yrs)	Height (cm)	Weight (kg)	Surface area (m^2)	Body Fat (%)	Predicted $V0_{2\,max}$ ($ml.kg^{-1}.min^{-1}$)	Day 1 GSL based on mass loss ($g.m^{-2}.h^{-1}$)	Day 6 GSL based on mass loss ($g\,m^{-2}.h^{-1}$)	Day 1 av HR during exe. (bpm)	Day 6 av HR during exe. (bpm)	Day 1 av. work rate ($W\,m^{-2}$)	Day 6 av. work rate ($W\,m^{-2}$)
m2	21	174 0	70 344	1 84	5 8	93 6	757	860	128	121	394	280
m4	28	176 0	71 067	1 86	18 8	60 0	579	670	138	143	312	420
m6	23	184 5	74 619	1 98	8 3	57 8	553	626	142	135	248	382
m7	20	178 0	76 882	1 95	12 2	59 3	637	714	157	139	339	371
m9	29	181 5	83 660	2 07	18 8	67 6	615	692	137	135	427	485
m12	28	177 5	74 165	1 92	10 5	51 5	582	688	143	145	321	416
mean ± SD	**25 ± 4**	**178 6 ± 3 8**	**75 12 ± 4.8**	**1.94 ± 0.1**	**12 4 ± 5.4**	**64 9 ± 14.9**	**621 ± 73**	**708 ± 80**	**141 ± 9**	**136 ± 9**	**340 ± 63**	**392 ± 68**

7.3.2 Environmental Conditions

Acclimation experiments were conducted in a climatic chamber at 45°C and 20% relative humidity with a 1 $m.s^{-1}$ wind speed.

7.3.3 Heart Rate and Work Rate

Mean work rate and mean heart rate over all three exercise bouts, and mean heart rate during rest were plotted for each day of acclimation (Figure 7.2).

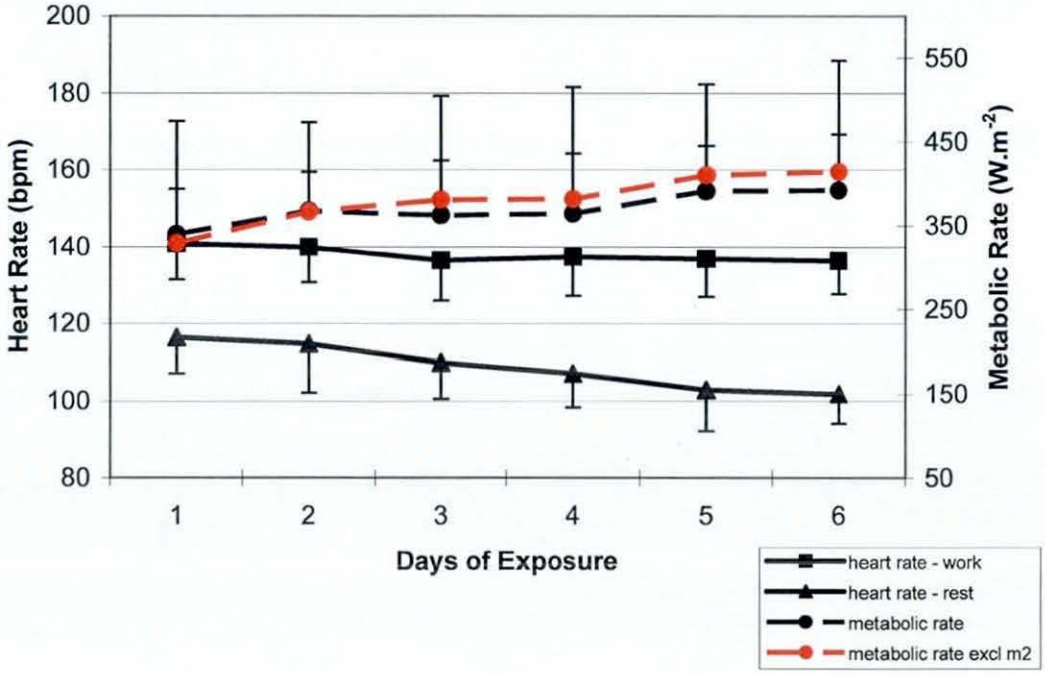


Figure 7.2. Mean heart rate (bpm) of all exercise bouts, mean heart rate during all rest periods, and mean work rate ($W.m^{-2}$) of all exercise bouts during each exposure in male athletes over 6 days of heat acclimation. An additional line shows the metabolic rates with participant m2 excluded.

As expected, work rate increased over the acclimation regime since a 1.4°C rise in T_{core} from BL was required during each exposure. A paired samples t-test was performed to compare mean metabolic rate (over all exercise bouts) from days one to six. Metabolic rate increased from 340 ± 63 $W.m^{-2}$ (659 ± 135 W) on day one to 392 ± 68 $W.m^{-2}$ (763 ± 155 W) on day 6, although this increase was not statistically significant. An increase of over 50 $W.m^{-2}$ (100 W) may however be considered biologically relevant given the duration and ambient conditions under which the participants were required to exercise.

Notably, participant m2 achieved the 1.4°C increase in T_{core} during each exposure but struggled to increase the intensity of cycling. Participant m2 showed a decline in metabolic rate during exercise (decreased external work) with values ranging from 394 $W.m^{-2}$ to 280 $W.m^{-2}$ on days one and six respectively. When data from participant m2 was excluded the increase in metabolic rate during exercise became significant from day one to six ($p < 0.01$). The removal of participant m2 from analysis of heart rate data produced little effect, with mean values rising by only 2-3 bpm during each exposure. Individual results will subsequently be reported for participant m2 where appropriate.

As the athletes acclimatised to the heat they had to work harder to achieve the desired increase in T_{core}, regardless of which, heart rate during exercise did not show a significant change between exposures. Within each exposure heart rate and metabolic rate were lower during exercise bout three since a number of participants either did not begin or did not finish the bout due to a T_{core} approaching 39°C (Table 7.2). Regardless of this, an average work rate was taken over the entirety of all bouts, reflecting both the intensity and duration of exercise. There were no significant differences in heart rate between exercise bouts however metabolic rate decreased significantly with progressive bouts (Including participant m2).

Table 7.2. Mean heart rate and mean metabolic rate of all participants during all 3 exercise bouts on days 1 to 6 of acclimation.

	Heart Rate (bpm)			Metabolic Rate ($W.m^{-2}$)		
Day	**bout 1**	**bout 2**	**bout 3**	**bout 1**	**bout 2**	**bout 3**
1	142	148	132	426	369	225
2	139	146	135	446	391	266
3	137	142	130	447	387	253
4	140	145	127	450	397	245
5	137	143	131	448	416	309
6	139	140	130	449	408	320
mean	**139**	**144**	**131**	**444*** **	**395*** **	**270*** **
sd	**2**	**3**	**3**	**9**	**16**	**37**

A significant decrease in mean heart rate during rest periods (one tailed) was present between day one and all other days (day three, $p < 0.01$; day four, $p < 0.001$; day five, $p < 0.01$; day six, $p < 0.01$) except day two with only day three becoming non

significant following Bonferroni correction. The mean change in heart rate (ΔHR) from day one to six was -5 ± 8 bpm during work and -15 ± 7 during rest (Figure 7.2). As expected no significant decrease in heart rate during work was present between exposures since the exercise intensity was progressively increased over the acclimation regime. The absence of an increase in heart rate is indicative of the cardiovascular adjustments associated with heat acclimation. The significant decrease in heart rate present during rest periods indicates a greater and more rapid recovery from exercise with acclimation, particularly given the increase in exercise intensity and/or duration. This is also true of a 'training effect' however since the participants were sub-elite athletes, a training effect was unlikely.

7.3.4 Core Temperature

Mean T_{core} of all participants over the course of 90 minute heat exposure was plotted for days one and six of the acclimation regime (Figure 7.3).

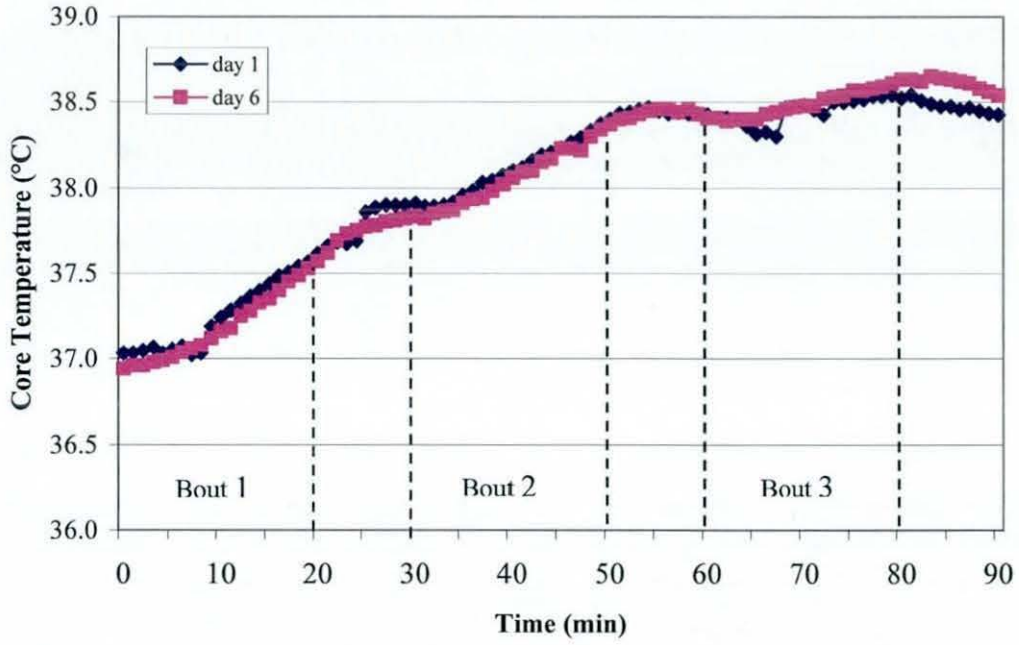


Figure 7.3. Core temperature (T_{re}) over the course of 90 minutes heat exposure on days 1 and 6.

T_{core} increased progressively during heat exposure, rising more rapidly during exercise bouts and showing a small plateau during rest periods. During both days one and six

T_{core} increased significantly from bout one to bout two ($p < 0.001$) but not during the final exercise bout. This was not unexpected since work rate was reduced during the 90 minute exposure to control T_{core} and achieve a level which the participant could maintain. No significant differences were present in T_{core} between exposures, achieving the desired maintenance of T_{core} through a progressive increase in work rate (Figure 7.2). Mean T_{core} values during exposure ranged from 37.9 ± 0.2 °C to 38.1 ± 0.1 °C during days five and three respectively.

7.3.5 Gross Sweat Loss

GSL was determined during each day of acclimation for all participants from the weight change during exposure and adjusted for fluid consumption. Corrections were made for metabolic and respiratory mass loss, as described in Chapter 2 (2.6.1. Gross sweat loss, equations 2.10-2.12). Mean (±SD) *GSL* ($g\ m^{-2}\ h^{-1}$) during each day of acclimation is presented in Figure 7.4. *GSL* of participant m6 on day five was excluded as an outlier, with a value of 470 $g\ m^{-2}\ h^{-1}$ which was considerably lower than all other values for that participant during acclimation.

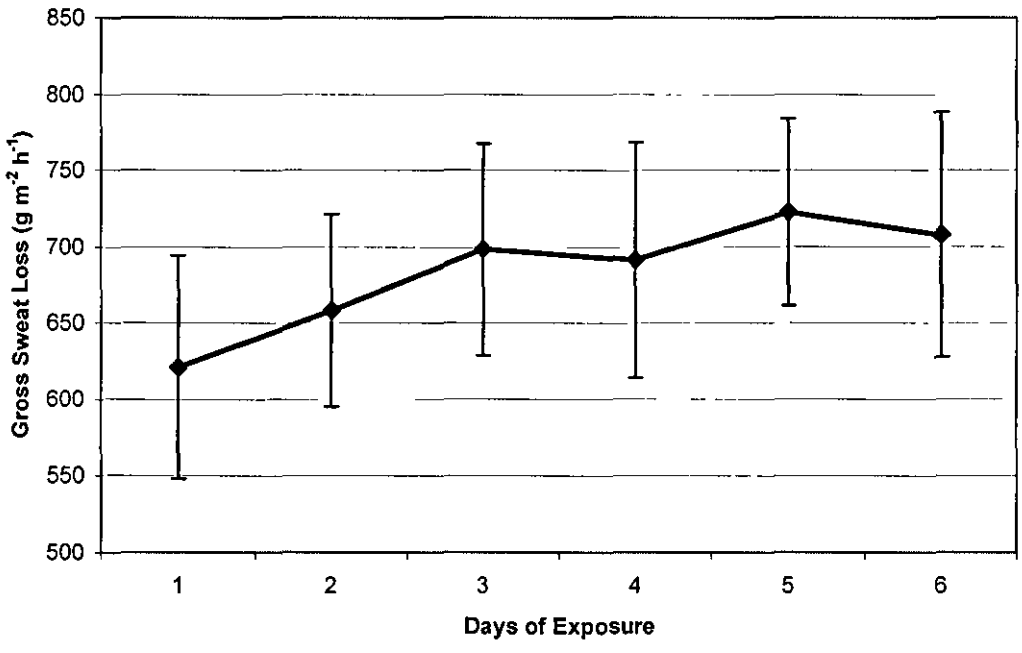


Figure 7.4. Mean gross sweat loss (±SD) of male athletes during six days of heat exposure and exercise.

The large variation in *GSL* between participants is evident from the large standard deviation observed in Figure 7 4 To identify individual differences in the data, *GSL* is presented for each day of acclimation in both grams and grams per surface area (corrected and uncorrected for metabolic and respiratory losses) for all participants in Table 7.3 and Table 7 4 respectively. For further analysis only corrected values will be used unless otherwise stated

GSL increased during acclimation in all participants, with peak values observed as early as days three and four in participant m12 and m6 respectively. Only participants m2 and m9 showed their highest *GSL* values on day six. *GSL* was significantly higher (1 tailed) on days four ($p < 0\ 05$) and six ($P < 0\ 01$) compared to day one of acclimation following Bonferroni correction Without correction for multiple comparisons, *GSL* was significantly higher on all days except day two when compared to day one (days 3 $p < 0\ 05$; 4 $p < 0.001$; 5 $p < 0.01$, and 6 $p < 0.001$) *GSL* did not increase significantly with consecutive exposures. Participant m2 consistently showed a higher *GSL* than all other participants with values of 757 $g\,m^{-2}\,h^{-1}$ and 860 $g\,m^{-2}\,h^{-1}$ for days one and six respectively, despite the decrease in work rate previously discussed. The peak change in *GSL* over acclimation ranged from 86 $g\,m^{-2}\,h^{-1}$ in participant m6 to 159 $g\,m^{-2}\,h^{-1}$ for participant m12 (excluding m6 outlier on day 5), with a mean peak ΔGSL of 128 ± 40 $g\,m^{-2}\,h^{-1}$.

Table 7.3. Gross sweat loss (g) during acclimation in male athletes uncorrected (uc) and corrected (c) for metabolic and respiratory mass loss Significant differences in gross sweat loss from day one are denoted as # P ≤ 0 05, ## P ≤ 0 01, ### P ≤ 0 001, $ 0 1 > P ≥ 0 05 following Bonferroni correction

	Gross Sweat Loss (g)											
	day 1		day 2		day 3		day 4		day 5		day 6	
Participant	uc	c	uc	c	uc	c	uc	c	uc	c	uc	c
m2	2206	2093	2160	2040	2319	2226	2422	2326	2377	2276	2474	2378
m4	1705	1615	1680	1577	1896	1777	1945	1838	2115	1976	2002	1866
m6	1721	1645	1941	1806	1982	1850	1997	1865	1467	1337	1993	1861
m7	1971	1868	2177	2061	2207	2097	2179	2061	2247	2120	2219	2093
m9	2041	1904	2235	2081	2232	2073	2182	2021	2204	2041	2316	2143
m12	1772	1676	2030	1899	2272	2134	2048	1907	2149	2009	2120	1980
mean	**1903**	**1800**	**2037**	**1911**	**2151$^{\$}$**	**2026$^{\$}$**	**2129$^{\#\#\#}$**	**2003$^{\#\#\#}$**	**2093**	**1960**	**2187$^{\#\#\#}$**	**2054$^{\#\#\#}$**
median	**1872**	**1772**	**2095**	**1970**	**2220**	**2085**	**2114**	**1964**	**2177**	**2025**	**2170**	**2037**
SD	**202**	**187**	**205**	**195**	**171**	**174**	**173**	**181**	**320**	**324**	**188**	**196**

Table 7.4. Gross sweat loss (g m^{-2} h^{-1}) during acclimation in male athletes uncorrected (uc) and corrected (c) for metabolic and respiratory mass loss Significant differences in GSL from day one are denoted as # P ≤ 0 05, ## P ≤ 0 01, ### P ≤ 0 001, $ 0 1 > P ≥ 0 05 following Bonferroni correction

	Gross Sweat Loss (g m^{-2} h^{-1})											
	day 1		day 2		day 3		day 4		day 5		day 6	
Participant	uc	c	uc	c	uc	c	uc	c	uc	c	uc	c
m2	798	757	781	738	838	805	876	841	859	823	894	860
m4	612	579	603	566	680	638	698	660	759	709	718	670
m6	579	553	653	608	667	623	672	628	494	450	671	626
m7	672	637	743	703	753	715	743	703	767	723	757	714
m9	659	615	722	672	721	669	704	652	712	659	748	692
m12	615	582	705	659	789	741	711	662	746	697	736	688
mean	**656**	**621**	**701**	**658**	**741$^{\$}$**	**698$^{\$}$**	**734$^{\#\#}$**	**691$^{\#\#\#}$**	**723**	**677**	**754$^{\#\#\#}$**	**708$^{\#\#\#}$**
median	**637**	**598**	**714**	**666**	**737**	**692**	**708**	**661**	**753**	**703**	**742**	**690**
SD	**77**	**73**	**64**	**63**	**66**	**69**	**73**	**77**	**122**	**124**	**75**	**80**

7.3.6 Skin Temperature

An average $\overline{T}_{sk}$ was calculated for the duration of each exposure and a mean taken for all participants for each day of acclimation (Figure 7.5).

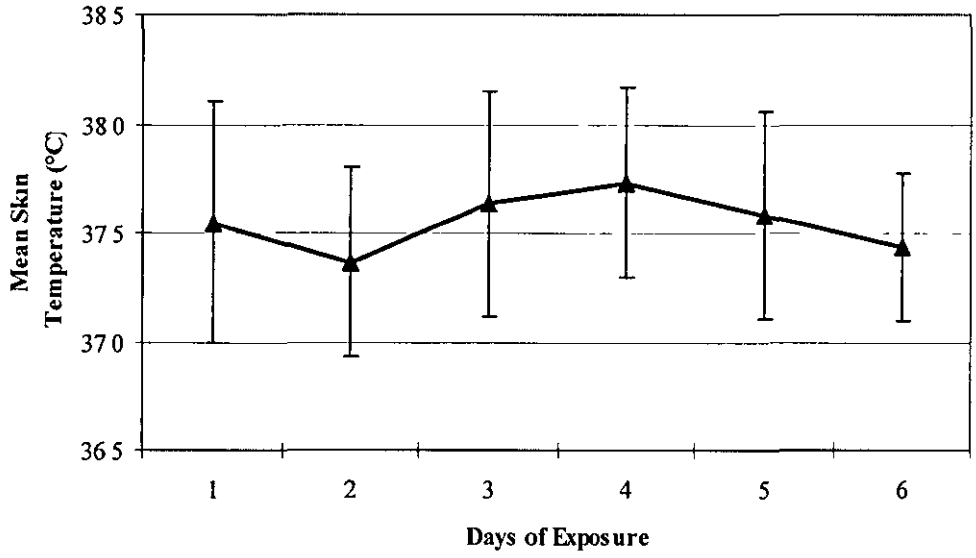


Figure 7.5. Average $\overline{T}_{sk}$ and mean work rate for each day of acclimation

No significant differences in $\overline{T}_{sk}$ were present between days 1 and 6 of acclimation. A significant decrease was present between day four and six, however the 0 3°C decrease was not of biological relevance.

7.4 Sweat Mapping: Pre - Post Acclimation Comparison

7.4.1 Core Temperature

Measurements of T_{core} were made sublingually and using core temperature (telemetry) pills As described in Chapter 4 (4.3.3. Core Temperature), some data points were missing due to the telemetry monitor failing to receive a signal from the core temperature pill. Results from the core temperature pill are therefore presented as the mean T_{core} over the final five minutes of I1 and I2, where all data were available. Mean T_{core} (pill), heart rate and work rate for each exercise intensity,

during both pre (mean of all experiments) and post acclimation sweat tests, are presented in Table 7.5

Table 7.5. Core temperature (telemetry pill), heart rate and work rate during pre and post acclimation sweat tests * denotes significance at the $p < 0.05$ level between pre and post acclimation values

	Tcore (°C)		Heart rate (bpm)		Work rate (% $V0_{2max}$)	
Time point	Pre	Post	Pre	Post	Pre	Post
baseline	37.2 ± 0.2	36.9 ± 0.4	65 ± 11	58 ± 7	-	-
I1 (26-30)	37.9 ± 0.1	37.6 ± 0.3	136 ± 2	132 ± 3*	54 ± 3	57 ± 5
I2 (56-60)	38.1 ± 3	37.9 ± 0.1	156 ± 3	157 ± 4	73 ± 4	76 ± 7

Work rate during each sweat test was determined by heart rate (I1 125-135 bpm, I2 150-160 bpm). Heart rate was significantly lower after acclimation at I1 however a difference of 4 bpm was not considered biologically relevant. Since there were no significant differences in running speed between pre and post acclimation tests (I1 pre 9.4 ± 2.0 km h^{-1}, post 9.9 ± 2.0 km h^{-1}, I2 pre 12.6 ± 2.5 km h^{-1}, post 13.1 ± 2.1 km h^{-1}) absolute work rate (W m^{-2}) was also not significantly different between experiments T_{core} was consistently lower during the post acclimation sweat test compared to pre acclimation values, but these differences were not significant at any stage. Sublingual temperature increased significantly during the pre acclimation sweat test ($p < 0.05$) from 36.4 ± 0.2°C to 36.8 ± 0.1°C but not during the post acclimation test The latter increased from 36.5 ± 0.2°C to 36.8 ± 0.2°C indicating no biologically relevant difference between experiments. No significant differences were present between pre and post acclimation sublingual temperature.

7.4.2 Gross Sweat Loss

GSL for both pre and post acclimation sweat tests over the duration of each experiment and for I1 and I2 separately are presented in Table 7.6. A significant increase (1 tailed) in *GSL* ($p < 0.01$) was present between pre and post acclimation sweat tests, rising from 449 ± 90 g m^{-2} h^{-1} to 546 ± 68 g m^{-2} h^{-1} All participants demonstrated an increase in *GSL*, with values ranging from 395 to 484 g m^{-2} h^{-1} during pre acclimation and 605 to 674 g m^{-2} h^{-1} following acclimation. The change

Table 7.6. Pre and post acclimation gross sweat loss (g m^{-2} h^{-1}) over the duration of sweat test and during intensity 1 and 2 separately corrected for metabolic and respiratory losses Pre and post acclimation surface area (SA) weighted sweat rate for all regions measured with pads (torso and arms) for I1 and I2 ** denotes a significant increase from pre to post acclimation

	Overall gross sweat loss ($g.m^{-2}.h^{-1}$)		**Gross sweat loss I1 ($g.m^{-2}.h^{-1}$)**		**Gross sweat loss I2 (g $m^{-2}.h^{-1}$)**		**SA weighted SR I1 ($g.m^{-2}.h^{-1}$)**		**SA weighted SR I2 ($g.m^{-2}.h^{-1}$)**	
Participant	pre	post	pre	post	pre	post	pre	post	pre	post
m2	605	674	484	440	767	987	516	721	696	1088
m4	358	520	267	295	500	821	275	543	430	790
m6	422	542	340	424	532	701	248	353	420	688
m7	414	499	268	338	609	714	277	569	461	762
m9	501	555	397	407	640	752	305	596	592	916
m12	395	484	343	352	526	660	251	320	524	598
mean ± SD	**449 ± 90**	**546 ± 68****	**350 ± 83**	**376 ± 56**	**596 ± 99**	**772 ± 118****	**312 ± 102**	**517 ± 153****	**521 ± 108**	**807 ± 174****

in *GSL* between pre and post acclimation sweat tests ranged from 10% to 31%. Notably, a significant increase was present between pre and post acclimation *GSL* at I2 ($p < 0.01$) but not at I1, whilst *SA* weighted *SR* from all measured regions increased significantly at both intensities ($p < 0.01$).

7.4.3 Regional Sweat Rate

Regional *SR* s of the torso and arms during the post acclimation sweat test are present in Table 7.7. A series of paired t-tests were used to compare regional *SR* s between exercise intensities. Results are presented both corrected and uncorrected for multiple comparisons.

Table 7.7. Descriptive statistics for all regions sampled at I1 and I2 in male athletes following acclimation. A comparison of sweat rates within each region between exercise intensities for both absolute and normalised data, corrected and uncorrected for multiple comparisons.

	Absolut sweat data (g m^{-2} h^{-1})										Significance level of intensity comparison	
	I1					I2						
	min	max	median	mean	SD	min	max	median	mean	SD	Absolute data	Normalised ratio data
shoulders	315	729	500	505	136	660	1183	838	873	186	***#	*
lat upper chest	302	576	415	442	108	485	1170	777	797	224	**#	-
centre ant upper	277	936	457	508	249	391	2205	944	1043	611	*	-
lat mid chest	314	638	473	472	119	585	888	686	708	107	**$	-
centre ant mid	393	919	661	674	216	698	1214	1076	1030	181	*	-
sides	248	722	434	449	175	480	1060	599	674	225	**#	-
ant lower	97	598	298	327	172	362	705	580	549	150	*	-
lat pos upper	477	902	789	729	168	996	1393	1097	1125	139	**#	-
centre pos upper	508	1582	836	928	393	1058	2042	1208	1367	374	**#	-
lat pos M-U	379	884	683	631	211	687	1331	908	940	236	**#	-
lat pos M-L	296	1086	741	694	297	647	1311	961	963	250	***##	-
centre pos mid	552	1667	1199	1178	402	1325	2411	1736	1772	396	**	-
pos lower	408	1439	748	860	391	359	1906	1059	1123	645	-	-
ant upper arm	145	553	340	344	142	308	709	498	513	148	***##	-
pos upper arm	149	468	367	342	114	301	806	617	589	178	**#	-
ant lower arm	198	624	448	424	160	393	919	673	655	222	**#	-
pos lower arm	183	562	485	427	150	415	973	731	703	222	**#	-

For conversion to other units divide by 600 to get mg cm^{-2} min^{-1}, or by 10,000 to get ml cm^{-2} h^{-1}
No correction *$P \leq 0.05$, **$P \leq 0.01$, ***$P \leq 0.001$,
Bonferroni correction # $P \leq 0.05$, ## $P \leq 0.05$, $ $0.1 > P \geq 0.05$

Similarly to the pre acclimation regional sweat data presented in Chapter 4 (4.3.6. Regional Sweat Rate), large variation between participants is clearly evident from the minimum and maximum values within each region. The regional patterns of sweating across the torso and arms were also similar to that observed during the pre acclimation body mapping. The highest *SR* at both intensities was observed on the central mid posterior torso with median values of 1199 and 1736 g m^{-2}.h^{-1} at I1 and I2 respectively. The lowest *SR* s were observed on the anterior lower torso at I1 and the anterior upper

arm at I2, with values of 498 and 298 g $m^{-2}.h^{-1}$ respectively. The posterior torso typically showed greater *SR* s than the anterior torso at both exercise intensities A proximal to distal increase in *SR* was evident on the arms at both exercise intensities, as observed in the pre acclimation data in Chapter 4. The *SR* s of the upper arms were typically lower than those of the torso, however the lower arm showed *SR* s similar to the anterior torso. When comparing absolute regional *SR* between exercise intensities, all regions except the posterior lower torso showed a significant increase The normalised data indicated no change in regional distribution with exception to a significant increase in the relative *SR* on the shoulders, however, this was not significant following Bonferroni correction

A comparison of pre and post acclimation regional *SR* s was performed on both absolute and ratio sweat data. Only the pre acclimation male body mapping data (Chapter 4) from participants involved in acclimation were used for comparison with post acclimation data A series of paired t-tests were conducted between pre and post values and are presented both with out without Bonferroni correction (Table 7 8) Most regions exhibited an increase in absolute *SR* following acclimation, with 12 of the 17 regions increasing significantly during I1 and 14 at I2. Following Bonferroni correction, only the sides and anterior lower arm remained significant at I1 ($p < 0.05$) and the shoulders, lateral upper back, lateral mid upper back, and posterior lower arm ($p < 0.05$) at I2 Interestingly, there was little difference in distribution between pre and post acclimation regional *SR* s. The lateral upper back ($p < 0\ 05$) and medial upper back ($p < 0\ 01$) normalised ratio values showed a significant decrease from pre to post acclimation, whilst the anterior upper arm ($P < 0\ 05$) showed a significant increase. At I2 the lateral upper back ($p< 0.01$) increased significantly form pre to post acclimation, and the anterior upper arm ($p < 0\ 01$), posterior upper arm ($p < 0.05$), and posterior lower arm ($p < 0\ 01$) showed a significant decrease. No values were significant at either intensity following Bonferroni correction, with only the posterior lower arm showing a p value less than 0.1.

Table 7.8. Significance level of pre-post acclimation comparison of absolute and ratio regional sweat data Grey shading indicates a significant decrease whilst no shading indicates a significant increase

	Significance level of pre-post acclimation comparison			
	Intensity 1		Intensity 2	
	Absolute data ($g\ m^{-2}\ h^{-1}$)	Normalised ratio data	Absolute data ($g\ m^{-2}\ h^{-1}$)	Normalised ratio data
shoulders	*	-	***#	-
lat upper chest	**$	-	*	-
med upper chest	-	-	-	-
lat mid chest	*	-	*	-
med mid chest	**	-	-	-
sides	**#	-	**$	-
ant lower	-	-	**	-
lat upper back	-	*	***#	**
med upper back	*	**	**	-
lat mid upper back	**$	-	**#	-
lat mid lower back	*	-	*	-
med mid back	-	-	**	-
pos lower back	-	-	-	-
ant upper arm	**	*	**$	**
pos upper arm	**	-	**$	*
ant lower arm	**#	-	**	-
pos lower arm	**	-	**#	**$

No correction *P ≤ 0 05, **P ≤ 0 01, ***P ≤ 0 001,

Bonferroni correction # P ≤ 0 05, ## P ≤ 0 01, ### P ≤ 0 001, $ 0 1 > P ≥ 0 05

7.4.4 Regional Skin Temperature

Pre acclimation data presented in Chapter 4 were re-analysed for the current analysis to include only the participants which completed the acclimation regime. A one-way repeated measures ANOVA and post hoc pairwise comparisons were performed on all regional T_{sk} data for all separate time points Based upon significant differences between regions and the biological relevance of those differences, the data were grouped appropriately for further analysis Data were grouped into corresponding right and left regions due to no significant right-left differences in the pre acclimation data and only two in the post acclimation data (post acclimation: BL, posterior upper torso $p < 0.05$, post I1, posterior lower torso $p < 0.05$) No significant right-left differences were present following Bonferroni correction Both pre and post acclimation T_{sk} data are presented in Table 7 9 and Table 7 10 respectively.

Table 7.9. Pre acclimation regional skin temperature of male body mapping participants at 5 measurement periods baseline (BL), pre I1 pad application (Pre I1), post I1 pad application (Post I1), pre I2 pad application (Pre I2), and post I2 pad application (Post I2) Significant changes within regions from the previous measurement period are indicated by the symbols listed below the table A significant decrease is indicated by grey shading ( )

		Skin Temperature (°C)				
Region		**BL**	**Pre I1**	**Post I1**	**Pre I2**	**Post I2**
UB	anterior medial upper	31 3	32 3	32 7*	32 9	33 5
	anterior lateral upper	31 6	31 7	32 2*	31 7*	32 8
	anterior medial lower	30 4	31 0	31 7**#	30 0**#	31 8
	anterior lateral lower	30 7	32 0	32 3*	31 6*	32 5
	posterior medial upper	31 9	32 4	33 4*	33 7	34 5
	posterior lateral upper	32 0	31 6	33 0**$	32 7*	34 0
	posterior medial lower	30 6	32 2	33 3***##	33 5	34 2
	posterior lateral lower	30 2	31 4	32 6**#	32.3*	33 5
	sides	30 6	31 5	32 5*	31.5*	32 9**#
AHF	anterior upper	32 4	31 8	32 9*	31 5*	32 7*
	posterior upper	31 6	31 9	32 9	31 8	32 9*
	anterior lower	31 4	31 7	33 0*	32 1	33 1
	posterior lower	31 7	31 9	32 8	32 5	33 0

No correction *P < 0 05, **P < 0 01, ***P < 0 001,
Bonferroni correction # P < 0 05, ## P < 0 05, ### P < 0 001, $ 0 1 > P ≥ 0 05

Table 7.10. Post acclimation regional skin temperature of male body mapping participants at 5 measurement periods baseline (BL), pre I1 pad application (Pre I1), post I1 pad application (Post I1), pre I2 pad application (Pre I2), and post I2 pad application (Post I2) Significant changes within regions from the previous measurement period are indicated by the symbols listed below the table A significant decrease is indicated by grey shading ( )

		Skin Temperature (°C)				
Region		**BL**	**Pre I1**	**Post I1**	**Pre I2**	**Post I2**
UB	anterior medial upper	33 4	31 8	33 1	31 5**#	33 2
	anterior lateral upper	32 9	31 3	32 8	30 5***##	32 9
	anterior medial lower	32 1	30 1	32 0	28 9***#	31 9*
	anterior lateral lower	32 7	31 2	32 7*	30 2**#	32 4
	posterior medial upper	33 1	32 7	34 6**#	33 0**#	35 2***##
	posterior lateral upper	32 8	31 5**#	34 2***##	32 0**#	35 0***##
	posterior medial lower	32 6	32 7	34 7***##	32 9***##	35 1***###
	posterior lateral lower	31 7	31 3	33 8***##	31 4***##	34 4***###
	sides	32 0	31 0	32 8**$	30 7**#	33 3**#
AHF	anterior upper	33 1	31 2	32 4	30 8**#	32 8*
	posterior upper	31 0	31 0*	32 6**$	31 8	33 5**$
	anterior lower	32 4	30 7**	32 1**#	30 8**	32 0
	posterior lower	31 7	31 0	32 2*	31 7	33 3**#

A series of paired t-tests were used to analyse changes in T_{sk} between measurement periods, and were corrected for multiple comparisons As observed in Table 7 9, no significant change in regional T_{sk} occurred during I1, however 11 out of 13 regions increase significantly during I1 pad application, three of which were significant following Bonferroni correction A significant decrease was observed in seven of the 11 regions during I2, with only three regions increasing significantly during I2 pad application This latter observation suggests that the pad application may not significantly impact upon T_{sk} since significant increases with pad application were not consistent across exercise intensity. The post acclimation regional T_{sk} observed in Table 7 10 indicates a greater degree of fluctuation with pad application compared to pre acclimation. A significant increase was observed in nine of the 11 regions during I1 pad application, followed by a significant decrease in 10 out of the 11 regions A significant increase in 10 out of 12 regions was observed following I2 pad application The mean increase of all regions at I1 was 0 9 ± 0.4°C and 1 7 ± 0.5°C for pre and post acclimation respectively, and 1.1 ± 0 4°C and 2 2 ± 0 6°C I2. The largest increase in T_{sk} was observed during I2 at the anterior medial lower torso in both pre and post acclimation data, increasing 1.8°C and 2.2°C respectively. The smallest increase during the pre acclimation testing was observed during at I1 the anterior lateral lower torso, rising by 0 3°C The anterior lower arms showed the smallest in crease in T_{sk} during post acclimation testing, rising 1 1°C. Despite the larger increases in regional T_{sk} during the post acclimation sweat test, only one significant difference was present between experiments. The anterior medial upper torso T_{sk} was significantly lower in the post compared to the pre acclimation sweat test at pre I2 pad application, owing to a larger decrease during I2 after the removal of I1 pads.

Regional T_{sk} within body segments responded similarly throughout the experiment Both pre and post acclimation data were grouped further into the anterior torso, posterior torso, and arms to provide an overview of T_{sk} responses during the time course of the experiment (Figure 7.6) The similarity in T_{sk} between pre and post acclimation data for each segment is evident, with exception to the lower post acclimation T_{sk} on the anterior torso (anterior medial upper, $p < 0.05$; anterior lateral

upper, p = 0.053; anterior lateral lower, p = 0.053) at pre I2 pad application. The fluctuations in T_{sk} with pad application are also clearly visible in Figure 7.6.

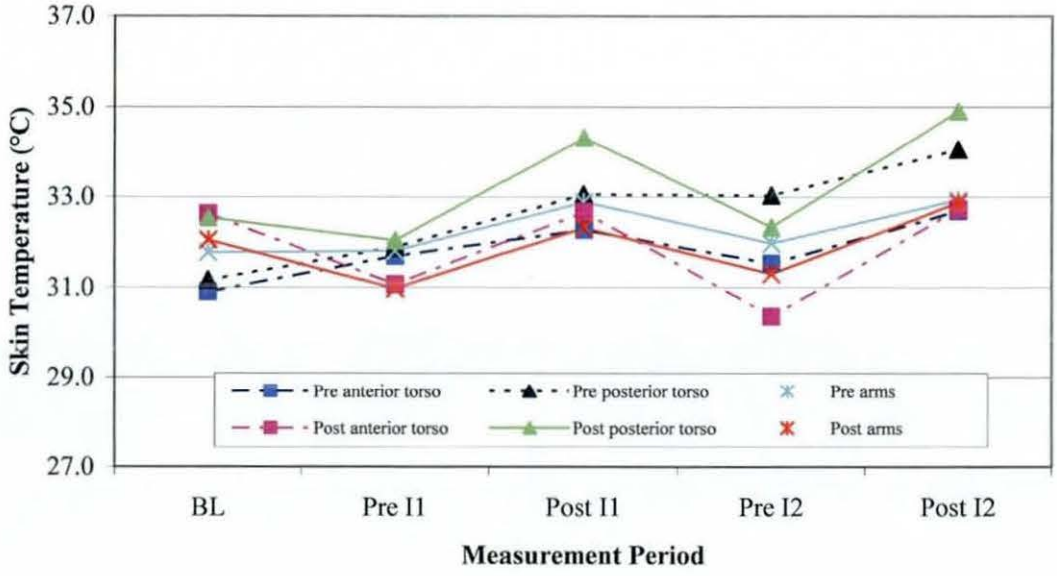


Figure 7.6. Pre and post acclimation regional skin temperature of male body mapping participants at 5 measurement periods: baseline (BL), pre I1 pad application (Pre I1), post I1 pad application (Post I1), pre I2 pad application (Pre I2), and post I2 pad application (Post I2).

A Pearson's r correlation was performed between regional T_{sk} and regional SR for each participant. As described in Chapter 4 (4.3.7. Regional Skin Temperature), within participant analysis was performed due to between participant factors confounding regional T_{sk} and SR. Correlations were performed between SR and both pre and post pad application T_{sk} at each exercise intensity due to significant differences between measurement periods. No strong correlation was observed between regional SR and regional T_{sk}, with the greatest r values being 0.54 at I1 and 0.21 at I2.

7.5 Discussion

7.5.1 Core Temperature

Under conditions of exercise in high ambient temperatures the body is placed under considerable thermal strain from both endogenous and exogenous heat. If sweating and its rate of evaporation from the surface of the skin is insufficient, heat accumulation will

occur. The thermoregulatory responses of the body to exercise and the concept of heat storage are described in more detail in chapter 4 (4.4.1 Core Temperature). The challenges from high ambient temperatures must however be emphasised, since the thermal gradient that drives K, C and R will be small or directed towards the body. A reversal of the thermal gradient from the skin to environment and core to skin occurs, causing heat storage in the body to increase further. The addition of exercise under such conditions places further strain upon the thermal, cardiovascular and fluid systems of the body.

As expected there was no significant difference in exercise T_{core} between the start and end of the acclimation regime since work rate was increased to elicit a predetermined increase in T_{core} during each exposure. Typically, T_{core} and heart rate, as measures of thermal strain, show a characteristic decrease with heat acclimation if both workload and ambient conditions are maintained at a constant level. To maximise the efficiency of the acclimation regime in the current study, thermal strain was progressively increased over consecutive heat exposures through an increase in exercise intensity. During the current regime, all participants illustrated characteristic responses to acclimation, maintaining the same heart rate and T_{core} for a progressively higher work rate with an accompanying increase in *GSL*.

No significant difference was present in T_{core} between pre and post acclimation sweat tests during either exercise intensity. Typically, acclimated individuals are able to maintain a lower T_{core} at a given T_a and/or workload compared to unacclimated individuals (Buono *et al.*, 1998). It may be that the athletes in the current study already possessed a high degree of acclimation due to their regular high intensity training, commonly referred to as a 'training effect'. The length of the acclimation period may also have proved insufficient to elicit a shift in thermoregulation towards greater efficiency, particularly given the fitness level of the participants. Cardiovascular and thermoregulatory adjustments typically occur within the first five days of acclimation before plateauing. There is however considerable variation between studies, with adjustments to acclimation occurring for much longer, reflecting the effectiveness of different acclimation regimes.

Mitchell *et al* (1976) emphasise the variation in individual responses in T_{core} (rectal) and heart rate during acclimation In particular, they describe one participant to behave as if already acclimated with no change in heat rate across nine days humid-heat acclimation and displaying a T_{core} on day one typical of other participants on day nine A similar phenomenon has been observed by several other authors, typically in individuals with a high cardiovascular fitness (Robinson *et al* , 1943, Piwonka *et al*, 1965). As described by Taylor and Cotter (2006), individuals may be high or low responders to heat acclimation with the period and extent of adaptation being highly dependent upon their pre acclimation state. Athletes represent low responders since they already posses a degree of heat acclimation and cardiovascular adjustments from high intensity training. However, although responding to heat exposure as if already acclimated, endurance trained individuals are able to attain more rapid adaptation during subsequent exposures. Conversely, individuals with a low cardiovascular fitness represent 'high responders' since they exhibit considerable adaptation with repeated heat exposure, however this occurs much more slowly, representing the 'high-but slowly-responding' individual (Taylor and Cotter, 2006)

7.5.2 Gross Sweat loss

Heat dissipation from the body during exposure to hot environments is largely reliant upon evaporation of sweat. It is well recognised that repeated heat exposure elicits an increase in sweating capacity (Fox *et al* , 1964, Nadel *et al* , 1974; Roberts *et al* ,1977, Patterson *et al* , 2003), however there is controversy surrounding the mechanisms involved in this adaptation. In the present study, *GSL* increased significantly both over the course of the acclimation regime and from pre to post sweat tests An increase from 449 ± 90 $g.m^{-2}.h^{-1}$ to 546 ± 68 $g\,m^{-2}\,h^{-1}$ ($p < 0\,05$) was observed from pre to post acclimation, with individual increases ranging from 10 to 31%. An associated reduction in onset to sweating (Libert *et al* , 1983) and a shift in T_{core} are also associated with attainment of an acclimated state (Winslow *et al*., 1937, Benzinger, 1969). Sweat onset was not measured in the present study using the modified absorbent technique. However, metabolic rate and T_{core} remained unchanged between pre and post acclimation experiments but a significantly higher *SR* was observed. This suggests no change in set point, as proposed by Libert *et al* (1983), who state that the increase in

SR observed with heat acclimation is due to an increase in thermal drive and not an alteration in the hypothalamic set point In contrast, Fox *et al* (1964) identified the importance of peripheral modification in sweating capacity. They observed an increase in regional sweat loss with local heating in the absence of heat acclimation, and the prevention of a regional sweat increase with local cooling during heat acclimation, with no evidence to suggest that local T_{sk} affected *GSL*. Fox *et al* (1964) therefore concluded that the increase in sweating capacity during heat acclimation results from a local training effect of the sweat gland and not an alteration in the sensitivity of the central nervous system. This is further supported by evidence of morphological changes at the glandular level during longer term acclimation (Sato et al , 1990) It would however appear that both central and peripheral modifications contribute to the adaptations observed with heat acclimation

7.5.3 Regional Sweat Rate

A significant increase from pre to post acclimation in absolute regional *SR* was present in 12 of the 17 regions measured at I1 and increased to 14 regions at I2. Following Bonferroni correction this decreased to 2 (sides and anterior lower arm) and 4 regions (shoulders, lateral upper back, lateral mid upper back, and posterior lower arm) at I1 and I2 respectively (3 regions, 0 01 > p > 0 05) This classic increase in *SR* with heat acclimation (Hofler, 1968, Candas *et al.*, 1983), coupled with a reduced onset time for initiation of sweating at corresponding or lower thermal drives allows maintenance of a lower T_{core} for a given workload A shift in sudomotor threshold represents a central modification in thermoregulation with a concomitant increase in sweat gland sensitivity and output per gland This indicates peripheral modification, or so called sweat gland 'training'. Both regulatory adaptations act to increase sweating capacity, however the degree to which an increased sensitivity of central and peripheral mechanisms to thermal stimuli contributes to sweating is under much debate (Libert *et al* , 1983). Results from the current study indicate an increase in sweat capacity but no decrease in T_{core} for the same work load.

No redistribution of *SR* was present at I1 following six consecutive days of hot-dry acclimation. The lateral and medial upper back showed a decrease in ratio values from

1.76 to 1.51 and 2 28 to 1 60 respectively from pre to post acclimation Conversely, the anterior upper arm increased from 0 47 to 0 65 Interestingly, normalised ratio values increased significantly at three of the four regions of the arms (uncorrected for multiple comparisons) at I2 This increase of sweat towards the limbs at the higher exercise intensity allows greater use of body surface area for evaporative cooling. This may indicate the development a beneficial adaptation which produces increased unity of skin wettedness over the body, and utilises the higher evaporation coefficients on the extremities in comparison to the torso. Redistribution of total sweat output was observed by Hofler (1986) following between 20 to 35 days heat acclimation, with those exposed to hot-humid conditions exhibiting an increase from *BL* values between 28-42% to post acclimation values ranging from 34-54% contribution of the limbs to total sweating Notably, changes in the distribution of sweat were not evident until 14 to 21 days of exposure, explaining why other investigators may have failed to observed this shift in sweating (Weiner, 1945, Cotter *et al* , 1997) Hofler (1986) only observed the phenomenon of redistribution towards the limbs following humid-heat but not dry-heat acclimation. The mechanism may therefore relate to skin wettedness, since conditions of restricted evaporation result in the level of evaporative cooling to remain in heat balance to be greater than the maximum evaporative potential of the environment. Cotter *et al* (1997) observed no post acclimation redistribution in regional *SR* following a 5 day controlled hyperthermia regime (T_{core} elevated 1.4°C from *BL*) under moderately humid heat (39 5°C, 59%) Since few adaptations to heat acclimation were present, the authors concluded that short term heat exposure in such conditions provides an inadequate adaptation stimulus for sudomotor adaptation A similar acclimation regime was used in the current study yet classic physiological adaptations to heat exposure and an indication of regional sweat redistribution to the arms (I2) was present. As concluded by Cotter *et al* (1997), an extended heat acclimation regime may elicit further augmented sudomotor adaptation and redistribution towards the limbs

One potential source of increase in *SR* may be the greater *SA* covered with absorbent pads during the post acclimation sweat test. The pre acclimation tests were performed progressively over three experiments (See Chapter 2· Experimental Methodology) in comparison to the torso and arms being measured simultaneously following acclimation This was however not thought to be problematic due to the short

measurement periods. Furthermore, neither T_{sk} or T_{core} were significantly higher at any measurement period during post acclimation testing, indicating no effect upon the thermal state of the body, and therefore regional or GSL.

7.5.4 Regional Skin Temperature

A beneficial decrease in T_{sk} during heat acclimation has been reported by many authors (Fox *et al*, 1963; Sato *et al*, 1990). Under conditions of high ambient temperature, an increase in cutaneous blood flow may result in a limited temperature gradient between the core and skin, which may not be efficient in heat loss (Johnson *et al*, 1986). Higher SRs and earlier onset observed with acclimation may enhance heat loss and reduce cutaneous blood flow, possibly through lower T_{sk} (Smolander and Holmér, 1991) In the present study, a significant increase in sweat loss was observed during heat acclimation, however no significant difference in T_{sk} was observed from day one to six. A significant decrease in $\overline{T}_{sk}$ of 0 3°C from day four to six of acclimation was present, however, this was not considered biologically relevant. It was concluded that six days of hot-dry heat acclimation using a controlled hyperthermia technique does not elicit a decrease in $\overline{T}_{sk}$ in male athletes This is supported by no significant differences between pre and post acclimation regional T_{sk}, with exception to one significant difference present at pre I2 pad application The duration of heat acclimation in the current study may not have been long enough to elicit the advantageous decrease in T_{sk} observed by some authors.

7.5.5 Conclusions

Six male Caucasian athletes completed six days of 90 minute hot-dry heat exposure involving a controlled hyperthermia acclimation regime. Following pre and post acclimation sweat tests, the following conclusions may be drawn

- Large inter and intra individual variability was observed in regional sweat loss during both the post acclimation sweat test, however, consistent patters were observed.

- The highest sweat rates were observed on the central and lower back in both pre and post acclimation sweat tests
- The lowest sweat rates were observed on the anterior lower torso at I1 and the upper arms during both intensities.
- No change in the distribution of sweat by acclimation was present at I1 but an indication of increased sweating efficiency was present at I2.
- No significant differences in regional skin temperature were present between pre and post acclimation sweat tests, with exception to the significant decrease of one region at pre I2 pad application
- Significant differences in T_{sk} were present between pre and post pad application measurements in a number of regions in both pre and post acclimation sweat tests. These differences were not thought to greatly influence regional sweat rate since they were not consistent between exercise intensities or between all regions

Chapter 8

Conclusions and Applications of Research

8 Chapter Summary

These pages provide a review of the main findings and notable points of discussion from the work conducted in this thesis. The applications of this research are also highlighted

8.1 Final Discussion and Conclusions

The aim of the present research was to produce a series of whole body sweat maps to establish regional sweat rates and distributions in Caucasian male athletes, female athletes, and untrained males in a moderate environment The effects of the presence and direction of wind upon regional sweat rates (SR) in addition to changes with hot-dry heat acclimation in male athletes were studied Regional sweat rate variations in humans are well recognised, however, to the knowledge of the author, quantitative research measuring large areas of the body simultaneously has not been conducted.

8.1.1 Effects of Wind Condition on Sweat Rate

The aim of the wind condition study presented in Chapter 3 was to determine whether the experimental conditions (i e wind from the front) used for the sweat mapping research in this thesis directly influenced regional SR s. Though gross sweat loss (GSL) was approximately 20% higher in the no wind (nw) condition than in the front or back wind (fw,bw), none of the observed differences achieved significance during the 30 minutes cycling in a moderate environment For the summed local SR s, nw SR was 48 to 69% higher than in the bw and fw condition respectively ($p<0.01$) Higher SR s in nw were expected due to lower convective heat loss and evaporative heat transfer

coefficient (h_e) requiring a higher SR to maintain the same core temperature (T_{core}) The lack of significance for GSL may have resulted from the relatively low work rate and short duration of exercise. Regional skin temperature (T_{sk}) was significantly higher during the nw condition too. The higher T_{sk} is required to increase the thermal gradient in this case, compensating for a lower convective and evaporative heat transfer coefficient. Most importantly for the overall research in this thesis the distribution of regional SR s between the anterior and posterior torso did not differ significantly between wind conditions. Also no significant differences were present in T_{sk} between the anterior and posterior torso within each wind condition This suggests that the 2 m s^{-1} front wind used in body sweat mapping did not significantly affect regional skin temperature or sweat distribution

8.1.2 Gross Sweat Loss and Metabolic Rate

Male athletes demonstrated a significantly higher GSL compared to both female athletes and untrained males at both I1 and I2 due to the choice of working at equal relative workloads Male athletes therefore worked at a significantly higher absolute work load compared to both other groups, with exception to the females during I1. The main points of discussion regarding these differences as described.

- Male and female athletes as a group demonstrated a similar sweat sensitivity (sweat increase per unit increase in work rate) at I1. No significant difference was present in T_{core}, however females had a significantly lower GSL. This can be explained by a significantly greater work rate in males than females at I1 and I2 ($p < 0.001$) in Watts. When normalised for surface area (W m^{-2}), significance was only present at I2, suggesting males were working harder at I1 because they were larger. Notably, a difference of 54 W.m^{-2} was observed between sexes at I1 which although not statistically significant, may be biologically relevant
- At I2 female athletes as a group showed a greater sweat sensitivity compared to male athletes, indicated by a significantly steeper regression slope ($p < 0.05$). This indicates a decrease in efficiency compared to the males as a group at a higher exercise intensity, producing more sweat per unit increase in work rate (W m^{-2}).

- Since male athletes were working at a significantly higher work rate ($p < 0.05$) than females at I2, it is unknown whether females would display a lower *GSL* than males for an equal metabolic rate at a higher exercise intensity. However, since females become less efficient compared to males with an increase in work rate, the difference in *GSL* may become less between groups In the present results females sweated 46% of that of males at I1 and 62% at I2 ($g\ m^{-2}\ h^{-1}$) whilst having a metabolic rate 87% that of males at I1 and 77% at I2 ($W\ m^{-2}$)
- In terms of heat balance, E_{max} was significantly lower than E_{req} for both male ($p < 0.001$) and female athletes ($p < 0.001$) at I1, however only for females at I2 ($p < 0.01$). Surprisingly, there was no significant difference in T_{core} between sexes despite the lower percentage of E_{req} achieved by the females Calculated E_{max} constituted 62% of E_{req} in males and 43% in females at I1, compared to 94% and 83% for males and females respectively at I2. This further supports a greater thermoregulatory efficiency in female compared to male athletes.
- Male athletes and untrained males as groups showed a similar sweat sensitivity, with the same increase in *SR* per unit increase in metabolic rate at I1 and I2. Male athletes showed a significantly higher $\dot{GSL}$ due to a higher absolute work rate at both intensities, however, no significant difference in T_{core} was present between groups This suggests a change in gain of the $SR - T_{core}$ relation observed with training, and fits well with the concept of T_{core} relating to relative work rate ($\%VO_{2\,max}$), and *SR* relating to absolute work rate.

8.1.3 Regional Sweat Rate

Male athletes showed significantly higher absolute *SR* s than both untrained males and female athletes for the same relative work load. Despite large variation in absolute regional *SR* s, consistent patterns were observed between individuals across all group

- The highest sweat rates were observed on the central and lower posterior torso, and the forehead
- The lowest sweat rates were observed on the fingers, thumbs and palms.

- A medial to lateral decrease in sweat rate was present on the torso, and a proximal to distal increase in sweat rate was present on the arms
- Sweat rate increased significantly with exercise intensity in most regions, with exception of the feet
- Sweat rates on the head showed a medial to lateral increase, however this difference was not significant, owing to a small sample size and large inter individual variation in absolute sweat rates

No significant difference in distribution of regional sweat rates was present between male athletes and untrained males, however female athletes showed a tendency for greater peripheral sweating, further suggesting a greater sweating efficiency compared to male athletes The marked regional variation in SR over the body in all groups could not be explained by regional sweat gland density reported in the literature but instead by sweat gland size and output per gland.

8.1.4 Regional Skin Temperature

A significant increase in T_{sk} was observed following pad application in a number of regions, however these regions were not consistent across exercise intensities or between groups. This was therefore not considered to significantly affect regional SR s, particularly considering the short measurement period. No significant correlation was observed between regional SR and regional T_{sk} in any group Regional T_{sk} therefore did not explain regional variation in sweat rate, possibly due to the narrow skin temperature range observed Regional differences in sudomotor sensitivity may be more useful in explaining regional SR s

8.1.5 Heat Acclimation

The heat acclimation study presented in Chapter 7 aimed to determine if any changes in quantity and distribution of regional SR s occurred in male athletes following six days of hot-dry heat acclimation. A comparison of pre and post acclimation sweat tests showed a significant increase in GSL ($p < 0\ 01$) for the same the same metabolic rate, with no significant difference in T_{core} This suggests a decrease in evaporative efficiency

since a lower T_{core} would be expected for a significantly higher SR at the same or lower thermal drive, unless blood flow changes were to occur. In addition, no significant difference in T_{sk} was observed between pre and post sweat tests, suggesting no increase in evaporative cooling with an increase in SR. No redistribution of SR was present at I1, however, normalised ratio values increased significantly at three of the four regions of the arms (uncorrected for multiple comparisons) at I2. This allows greater use of body surface area for evaporative cooling, possibly indicating the development of a beneficial adaptation which produces increased unity of skin wettedness over the body, and utilises the higher evaporation coefficients on the extremities in comparison to the torso. An extended heat acclimation regime may elicit further augmented sudomotor adaptation and redistribution towards the limbs.

8.1.6 Reference Sweat Measurement Sites

An important final point of discussion is the possibility of selecting only a few measurement sites of regional sweat rate as reference sites or in the prediction of GSL. The thigh and the chest are traditionally used as reference sites for sweat measurement using capsules In the present series of studies the thigh consistently showed a similar normalised SR between groups and may therefore be a good choice. Normalised values for I1 and I2 respectively were 0 96 and 0.89 for male athletes, 1.19 and 1 13 for female athletes, and 0.94 and 0.85 for untrained males, which were good representatives of GSL. To assess the suitability of different sites as reference sites a multiple regression was performed with all regions as predictors for GSL ($g\,m^{-2}\,h^{-1}$) to calculate the maximum amount of variance which could be explained by regional SR. A model including all local SR's explained 94% of the variance in GSL. Since there are a large number of good predictors, selecting only small number to predict GSL would be extremely useful for future thermophysiological research. To identify the regions which would best predict GSL a simple correlation was performed between GSL ($g\,m^{-2}\,h^{-1}$) and each regional SR of the combined data for all groups at both exercise intensities The Pearson's r correlation coefficients for all regions may be observed in Table 8 1, presented in order of r^2 value

Table 8.1. Pearson's r correlation coefficients and r^2 values for different regional sweat rates as predictors of gross sweat loss

Region	r	r2
pos lower leg	0.86	0.74
ant lower arm	0.86	0.74
lat upper back	0.86	0.73
med upper back	0 85	0.73
lat mid upper back	0.85	0.72
med upper leg	0.85	0.72
lat upper leg	0 85	0.72
ant med lower leg	0 85	0 72
pos lower arm	0 84	0 71
ant upper leg	0.84	0.70
ant lat lower leg	0 83	0.70
ant upper arm	0 82	0 67
pos upper leg	0 81	0 65
pos upper arm	0 80	0 64
med mid back	0.79	0 63
pos lower back	0.78	0 62
gluts	0.78	0 60
lat mid lower back	0.77	0 59
sides	0 76	0 58
lat mid chest	0.75	0 56
med ankle	0 75	0 56
shoulders	0.73	0.53
med mid chest	0 72	0 52
upper chest	0.70	0 49
back hand	0.67	0.45
palms	0 66	0.43
lat ankle	0 65	0 43
ant lower	0 61	0 37
thumbs	0 59	0.35
sole	0.53	0 28
fingers	0 40	0.16
top foot	0 34	0 11
toes	0.32	0 10
heel	0.26	0 07

A region with an r value greater than or equal to 0.85 was considered to have a strong correlation Any of the top eight regions listed in Table 8.1 would therefore be acceptable if a single site of measurement were to be used for the prediction of *GSL*. However, using a small number of sites would be useful in predicting *GSL* whilst

minimising the unexplained variance. A stepwise multiple regression was performed using all regions as predictors to assess the most influential regions at consecutive stages of the regression, as indicated by the partial correlations. The model produced by SPSS used four predictors, 1) anterior lower arm, 2) posterior lower leg, 3) lateral ankles, 4) centre posterior upper torso The resultant model was

$$GSL\left(g\,m^{-2}\,h^{-1}\right) = 124\,09 + \left(0\,26\ \text{ant lower arm}\right) + \left(0.38 \cdot \text{pos lower leg}\right) + \left(0.21 \cdot \text{lat ankles}\right) + \left(0.12 \cdot \text{medial upper back}\right) \quad (8.1)$$

explaining 85% of the variance in GSL. However, the practicality of the measurement sites must be considered. For example, the lateral ankles would be impractical to measure, particularly if a capsule method were used. A further stepwise multiple regression was performed, excluding impractical measuring sites Based on measurements at the anterior lower arm, lateral upper leg, and central posterior upper torso, the model was.

$$GSL\left(g\,m^{-2}\,h^{-1}\right) = 139\,59 + \left(0\,31\ \text{ant lower arm}\right) + \left(0\,35 \cdot \text{lat upper leg}\right) + \left(0.12 \cdot \text{medial upper back}\right) \quad (8\,2)$$

explaining 82% of variance in GSL These three sites may therefore be useful locations for regional sweat measurement as a good predictor of GSL.

8.2 Applications of research

The present research was part funded by the commercial sports clothing and equipment manufacturer Adidas and directly applied to the design of sports clothing to produce their CLIMA365 range. The regional variation in sweat rate over the body was interpreted by Adidas in conjunction with body temperature maps for decisions regarding the placement of ventilation and materials with varied properties to maximise evaporative cooling and thermal comfort The direct application of the body sweat maps for the design of sports clothing may be observed in Figure 8 1 Notably, the design has incorporated a panel of material allowing ventilation down the central back to accommodate for the high regional sweat rate in that location.

Figure 8.1. Translation of body mapping research into running apparel design.

The differences in both absolute sweat rates and distribution between male and female athletes allows gender specific clothing to be designed. Sweat map templates have been produced commercially from the present data for the design of both elite and mass market clothing design.

The present body mapping data may similarly be used for protective clothing design. Combining physiological data with mathematical models of thermoregulation and occupational work limits, performance and thermal comfort may be improved. For example, improving ventilation on the central back in NBC protective clothing to improve evaporative heat loss and help reduce the risk of heat stress. Finally, the data could be applied to thermal sweating manikins to improve realism of the typically uniform sweat rates which are currently used.

Chapter 9

Recommendations for Future Work

The research in this thesis was of an applied and largely exploratory nature. A modified absorbent technique was used to measure regional sweat rates over the whole body in three groups of Caucasians, male athletes, female athletes, and untrained males The results from the present data give rise to further research questions, some of which are described below.

1. The modified absorbent technique has produced some of the most comprehensive quantitative data measuring regional sweat rates over the whole body. This technique may be used further to gain detailed data on regional sweat rates and distributions in other participant groups, over a range of environmental conditions, and during other exercise modes and work rates. Sweat mapping of untrained females was not conducted within this thesis, however, a comparison with the present female athlete data would be of interest No significant difference in regional sweat distribution over the body was present between trained and untrained males, however it is unknown if differences in intra segmental sweat rate are present between trained and untrained females

2 Further research regarding regional sweat rates and subject matching is required Limited studies employ the same absolute work rate between groups nor strictly match their participants for cardiovascular fitness and morphology. The present research took an applied approach to assess differences in regional sweat rates between groups. Since 'typical' individuals were used from each population, rather than matching participants, questions regarding regional sweat rates between sexes still remain. A highly controlled, more mechanistic approach would help answer questions regarding the true thermoregulatory differences between sexes.

3. A direct comparison with ventilated capsule work would be of use to assess variability between techniques The ventilated capsule is the most widely used quantitative measure of regional sweat rate, however, measures only a small surface area of skin. The modified absorbent method has the advantage of measuring large surface areas of skin simultaneously, however cannot continuously measure sweat loss over time. Each method has its advantages and limitations, making them suitable for different applications.

4. The absorbent technique may be used in the analysis of regional sweat composition since the sweat is collected by the pads during testing. A considerable body of research is available regarding sweat composition and its alterations with exercise intensity, duration, and heat acclimation. However, whole body techniques are traditionally used, preventing regional analysis Since there are such marked differences in regional sweat rate over the body, regional differences in sweat composition may also be present

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Appendices

Appendix A

Body Sweat Mapping

INFORMED CONSENT FORM
(to be completed after Participant Information Sheet has been read)

The purpose and details of this study have been explained to me I understand that this study is designed to further scientific knowledge and that all procedures have been approved by the Loughborough University Ethical Advisory Committee.

I have read and understood the information sheet and this consent form.

I have had an opportunity to ask questions about my participation.

I understand that I am under no obligation to take part in the study

I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing

I understand that all the information I provide will be treated in strict confidence

I agree to participate in this study.

Your name _____

Your signature _____

Signature of investigator _____

Date _____

HEALTH SCREEN QUESTIONNAIRE FOR STUDY VOLUNTEERS **Name/Number**

.....

- **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 [*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 **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 (HRT)?	Yes		**No**	

Health Screen Questionnaire for Use of Radio Pills

Name/Number.....

The following questions are relevant to the use of the ingestible temperature sensor, or "temperature pill". It is important that volunteers participating in research studies involving this device are currently in good health and have had no significant medical problems in the past. This is to ensure (i) their own continuing well-being and (ii) to avoid the possibility of individual health issues confounding study outcomes.

Please complete this brief questionnaire to confirm fitness to participate

1. At present, or in the past **have you had any of the following health problems:**

   (a) Any known or suspected obstructive disease of the gastrointestinal tract, including but not limited to diverticulitis and inflammatory bowel disease.
   Yes ☐ No ☐

   (b) Any inflammatory bowel disease
   Yes ☐ No ☐

   (c) A history of disorders or impairment of the gag reflex.
   Yes ☐ No ☐

   (d) Any previous gastrointestinal surgery.
   Yes ☐ No ☐

   (e) Are you or might you undergo Nuclear Magnetic Resonance (NMR) scanning during the period that the disposable temperature sensor is within the body.
   Yes ☐ No ☐

   (f) Any hypomotility disorders of the gastrointestinal tract including but not limited to Illus
   Yes ☐ No ☐

Appendix B

SKINFOLD MEASUREMENT SHEET

Subject: _____

ALL MEASUREMENTS TO BE MADE ON THE RIGHT SIDE OF THE BODY

		SKF measurement (mm)			
Subjects	**SKF site**	**sample 1**	**sample 2**	**sample 3**	**Mean (mm)**
Male and Female Athletes	triceps				
	anterior suprailiac				
HM	abdomen				
HM	thigh				
Male Athletes Only HM	chest				
	midaxillary				
	subscapular				
				SUM	

SKF REGRESSION EQUATIONS

(Caucasian)

Male athlete Db (g/cc) = 1 112 - 0 00043499 (∑7SKF) + 0 00000055 (∑7SKF)2 - 0 00028826 (age)

Female athlete Db (g/cc) = 1 096095 - 0 0006952 (∑4SKF) + 0 0000011 (∑4SKF)2 - 0 0000714 (age)

Healthy Males (HM) Db (g/cc) = 1 109380-0 0008267 (∑3SKF) + 0 0000016 (∑3SKF)2 - 0 0002574 (age)

Sweat Mapping: Anthropometric Measurements and Pad Calculations

Anatomical Measurement Descriptions: Upper Body

location	measurement description
biacromial diameter	distance between the right and left acromion processes
upper body length	distance between the right acromion process and the height of the right anterior iliac spine
upper arm circum	the circumference at the mid point of the upper arm (mid point of the distance from the superolateral surface of the acromion process to the posterior surface of the olecranon process of the ulna)
upper circum	circum at the level of the upper body length * 0 62
mid-upper circum	circum at the level of the upper circumference height / 2
mid-lower circum	circum at the level of the mid-upper circum height / 2
lower circum	circum at the level of the right and left anterior superior iliac spine

Measurement Sheet for Upper Body Pad Dimensions

Subject: _____

Location	cm	Location	cm
biacromial diameter		upper body length	
r upper arm circum		l upper arm circum	
upper circum		mid-upper circum	
mid-lower circum		lower circum	

Clothing Item	Size
T-shirt	
Zip t-shirt	
Running shorts	

Females Only - Bra Size: _____

upper arm circum Height = upper arm length r =
l =
upper circum Height = upper body length * 0 62 =
mid-upper circum Height = upper circum Height / 2 =
mid-lower circum Height = mid-upper circum Height / 2 =
(lower circum Height = level of ant Sup Iliac spine)

ANTERIOR & POSTERIOR WIDTH CALCULATIONS FOR ABSORBENT PADS

anterior upper width = upper circum * 0 32
anterior mid width = mid-upper circum * 0 37
anterior lower width = lower circum * 0 4

---

posterior upper width = upper circum * 0 4
posterior mid-upper width = mid-upper circum * 0 43
posterior mid-lower width = mid-lower circum * 0 37
posterior lower width = lower circum * 0 38

ABSORBENT PAD DIMENSION CALCULATION SHEET: UPPER BODY

Subject _____

r shoulder

	biacromial diameter *
width:	**0.32**
	upper arm circum.
med side:	***0.54**
	arm circum *
lat side:	**0.81**

ant/pos side: biacromial diameter * 0.12

l shoulder

	biacromial diameter *
width:	**0.32**
	upper arm circum.
med side:	***0.54**
	arm circum *
lat side:	**0.81**

ant/pos side: biacromial diameter * 0.12

MALE ONLY

r ant upper

med height· upper body length * 0.38

	upper body length *
lat height:	**0 31**

upper width: no 'upper side' but width is same as centre ant upper

lower width: anterior mid width / 3

centre ant upper

	upper body length *
height:	**0.38**

upper width: anterior upper width / 3

lower width: anterior mid width / 3

l ant upper

med height: upper body length * 0.38

	upper body length *
lat height:	**0 31**

upper width: no 'upper side' but width is same as centre ant upper

lower width: anterior mid width / 3

FEMALE ONLY

r/l ant Upper

lat height: upper body length * 0.18

med height· upper body length * 0.22

width: upper circum. * 0.14

r ant mid

height: upper body length * 0.34

upper width: anterior mid width / 3

lower width: anterior lower width / 3

centre ant mid

height: upper body length * 0.34

upper width: anterior mid width / 3

lower width: anterior lower width / 3

l ant mid

height: upper body length * 0.34

upper width: anterior mid width / 3

lower width: anterior lower width / 3

r side

height: upper body length * 0.55

upper width: upper circum. * 0.07

lower width: lower circum. * 0.09

l side

height: upper body length * 0.55

upper width: upper circum. * 0.07

lower width: lower circum. * 0.09

ant lower

height: upper body length * 0.10

width: = anterior lower width

---

r pos upper

med height: upper body length * 0.38

lat height: upper body length * 0 31

upper width: no 'upper side' but width is same as centre pos upper

lower width: posterior mid-upper width /3

centre pos upper

height: upper body length * 0 38

upper width: posterior upper width / 3

lower width: posterior mid-upper width / 3

l pos upper

med height: upper body length * 0.38

lat height: upper body length * 0.31

upper width: no 'upper side' but width is same as centre pos upper

lower width: posterior mid-upper width /3

r pos mid upper

height: centre pos mid pad height / 2

upper width: posterior mid-upper width / 3

lower width: poterior-mid-lower width / 3

l pos mid upper

height: centre pos mid pad height / 2

upper width: posterior mid-upper width / 3

lower width: poterior-mid-lower width / 3

r pos mid lower

height: centre pos mid pad height / 2

upper width: posterior mid-lower width / 3

lower width: posterior lower width / 3

l pos mid lower

height: centre pos mid pad height / 2

upper width: posterior mid-lower width / 3

lower width: posterior lower width / 3

centre pos mid

height: upper body length * 0.34

upper width: posterior mid-upper width / 3

lower width: posterior lower width / 3

pos lower

height: upper body length * 0.10

width: = posterior lower width

PLASTIC SHEETING CALCULATIONS: UPPER BODY

Subject: _____

height upper body height + 15cm
biacromial diameter: biacromial diameter + 16cm
upper width (upper circum / 2) + 16
mid-upper width (m-u circum / 2) + 16
mid-lower width (m-l circum / 2) + 16
lower width (lower circum /2) + 16

ANATOMICAL MEASUREMENT DESCRIPTIONS: LEGS, FEET, AND BUTTOCKS

Location	Measurement description
upper leg length	distance from the anterior superior iliac spine to the proximal edge of the patella
lower leg length	distance from the distal edge of the patella to the level of the proximal surface of the medial and lateral malleoli

MEASUREMENTS FOR ABSORBENT PAD DIMENSIONS AND PLASTIC SHEETING

Absorbent Pad Dimension Measurements

Location	Pad Measurement Description
anterior upper leg length	distance from the anterior superior iliac spine to the proximal edge of the patella
anterior lower leg length	distance from the distal edge of the patella to the level of the proximal surface of the medial and lateral malleoli
upper leg upper circum	circumference of the upper leg at the height of the top of the absorbent pad (upper leg length*0 6)
upper leg· mid circum	circumference of the upper leg at the midpoint of the absorbent pad (upper leg length*0 6/2)
upper leg· lower circum	circumference of the upper leg directly at the height of the proximal edge of the patella (level of the bottom of the absorbent pad)
lower leg upper circum	circumference of the lower leg at the height of the distal edge of the patella
lower leg· mid circum	circumference at the midpoint of the lower leg (lower leg length/2)
lower leg lower circum	circumference of the lower leg at the level of the proximal surface of the medial and lateral malleoli
lower leg· anterior/posterior division	medial malleolus to medial condyle of femur lateral malleolus to lateral condyles of femur
anterior lower leg· upper width	width across anterior division of the leg at the height of the distal edge of the patella
posterior lower leg upper width	width across posterior division of the leg at the height of the distal edge of the patella
anterior lower leg mid width	width across anterior division of the leg at the midpoint of the lower leg (lower leg length/2)
posterior lower leg mid width	width across posterior division of the leg at the midpoint of the lower leg (lower leg length/2)
anterior lower leg lower width	width across the anterior division of the leg at the level of the proximal sufrace of the medial and lateral malleoli
posterior lower leg lower width	width across the posterior division of the leg at the level of the proximal surface of the medial and lateral malleoli
hip circum ant sup Iliac spine	circumference of the waist at the level of the anterior superior iliac spine
hip circum· head of femur	circumference of the waist at the level of the head of femur

Measurement Sheet for Leg and Buttock Pad Dimensions

Subject: _____

Location	cm	Location	cm
right anterior upper leg length		left anterior upper leg length	
right anterior lower leg length		left anterior lower leg length	
right upper leg upper circum		left upper leg upper circum	
right upper leg mid circum		left upper leg mid circum	
right upper leg lower circum		left upper leg lower circum	
right lower leg upper circum		left lower leg upper circum	
right lower leg mid circum		left lower leg mid circum	
right lower leg lower circum		left lower leg lower circum	

Location	cm	Location	cm
right lower leg anterior upper width		left lower leg anterior upper width	
right lower leg posterior upper width		left lower leg posterior upper width	
right lower leg anterior mid width		left lower leg anterior mid width	
right lower leg posterior mid width		left lower leg posterior mid width	
right lower leg anterior lower width		left lower leg anterior lower width	
right lower leg posterior lower width		left lower leg posterior lower width	
ant. Iliac spine circum		head of femur circum	

Clothing Item	Size
running pants	
running shorts	
t-shirt	

u leg u circum = u leg length * 0 6 R= L=
u leg m circum = u pad length / 2 R= L=
l leg m circum = l leg length / 2 R= L=

ABSORBENT PAD CALCULATION SHEET: LEGS

r ant upper

height: r. upper leg length * 0 6

upper width: r. upper circum. / 4

mid width: r. mid circum. / 4

lower width: r. lower circum. / 4

r pos upper

height:

upper width: **as above**

mid width:

lower width:

r med upper

height:

upper width: **as above**

mid width:

lower width:

r lat upper

height:

upper width: **as above**

mid width:

lower width:

r ant med lower

height: = r. lower leg length

upper width: r. lower leg anterior upper width / 2

mid width: r. lower leg anterior mid width / 2

lower width: r. lower leg anterior lower width / 2

r ant lat lower

height:

upper width: **as above**

mid width:

lower width:

r pos lower

height: = r. lower leg length

upper width: = r. lower leg posterior upper width

mid width: = r. lower leg posterior mid width

lower width: = r. lower leg posterior lower width

---

l ant upper

height: l. upper leg length * 0.6

upper width: l. upper circum. / 4

mid width: l. mid circum. / 4

lower width: l. lower circum. / 4

l pos upper

height:

upper width: **as above**

mid width:

lower width:

l med upper

height:

upper width: **as above**

mid width:

lower width:

l lat upper

height:

upper width: **as above**

mid width:

lower width:

l ant med lower

height: = l. lower leg length

upper width: l. lower leg anterior upper width / 2

mid width: l. lower leg anterior mid width / 2

lower width: l. lower leg anterior lower width / 2

l ant lat lower

height:

upper width: **as above**

mid width:

lower width:

l pos lower

height: = l. lower leg length

upper width: = l. lower leg posterior upper width

mid width: = l. lower leg posterior mid width

lower width: = l. lower leg posterior lower width

PLASTIC SHEETING CALCULATION SHEET: LEGS

Subject: _____

Right upper leg
height· upper pad length + 5cm
upper width. (upper circum / 2) + 10
mid width· (mid circum / 2) + 10
lower width (lower circum / 2) + 10

Left upper leg
height upper pad length + 5cm
upper width (upper circum / 2) + 10
mid width (mid circum / 2) + 10
lower width (lower circum / 2) + 10

Right lower leg
height lower pad length + 5cm
upper width (upper circum / 2) + 10
mid width· (mid circum / 2) + 10
lower width (lower circum / 2) + 10

Left lower leg
height lower pad length + 5cm
upper width· (upper circum / 2) + 10
mid width (mid circum / 2) + 10
lower width (lower circum / 2) + 10

ANATOMICAL MEASUREMENT DESCRIPTIONS: ARMS AND HANDS

location	measurement description
upper arm length	distance from the superolateral surface of the acromion process to the posterior surface of the olecranon process of the ulna
lower arm length	distance from the posterior surface of the olecranon process of the ulna to the styloid process of the ulna

MEASUREMENTS FOR ABSORBENT PAD DIMENSIONS AND PLASTIC SHEETING

Absorbent Pad Dimension Measurements

Location	Pad Measurement Description
upper arm length	distance from the superolateral surface of the acromion process to the posterior surface of the olecranon process of the ulna * 0 7
lower arm length	distance from the posterior surface of the olecranon process of the ulna to the styloid process of the ulna
upper arm upper circum	circumference of the upper arm at the height of the top of the absorbent pad (upper arm length * 0 7)
upper arm mid circum	circumference at the midpoint of the upper arm pad length (upper arm length * 0 7/2)
upper arm lower circum	circumference of the upper arm at the height of the superior surface of the olecranon process of the ulna
lower arm upper circum	circumference of the lower arm at the height of the olecranon process of the ulna
upper arm mid circum	circumference at the midpoint of the lower arm (lower arm length/2)
lower arm lower circum	circumference of the lower arm at the height of the superior surface the styloid process of the ulna

Anterior and Posterior pad widths are produced by dividing the circumferences at the 3 points by 2.

Plastic Sheeting Measurements

Location	Description
upper arm length	(distance from the superolateral surface of the acromion process to the posterior surface of the olecranon process of the ulna * 0 7) + 5cm
lower arm length	distance from the posterior surface of the olecranon process of the ulna to the styloid process of the ulna + 5cm
upper arm upper width	upper arm upper circumference + 12cm (extra sheeting to allow tying at top of arm)
upper arm mid width	upper arm mid circumference + 8cm
upper arm lower width	upper arm lower circumference + 8cm
lower arm upper width	lower arm upper circumference + 8cm
lower arm mid width	lower arm mid circumference + 8cm
lower arm lower width	lower arm lower circumference + 8cm

Divide all widths by 2 when tracing on plastic sheeting due to it being folded in half

Measurements for Ankle Pad Dimensions

Right ankle **Left ankle**

Location	cm	Location	cm
circum of ankle at the height of the proximal surface of the medial and lateral malleoli		circum of ankle at the height of the proximal surface of the medial and lateral malleoli	
distance from the bottom of the heel to the proximal surface of the lateral malleolus		distance from the bottom of the heel to the proximal surface of the lateral malleolus	
distance from the bottom of the heel to the proximal surface fo the medial malleolus		distance from the bottom of the heel to the proximal surface fo the medial malleolus	

Measurements for Foot Pad Dimensions
Draw around each foot onto paper and use for measurements

Measurement Sheet for Arm Pad Dimensions

Subject: _____

Location	cm	Location	cm
right upper arm length		left upper arm length	
right lower arm length		left lower arm length	
right upper arm upper circum		left upper arm upper circum	
right upper arm mid circum		left upper arm mid circum	
right upper arm lower circum		left upper arm lower circum	
right lower arm upper circum		left lower arm upper circum	
right lower arm mid circum		left upper arm mid circum	
right lower arm lower circum		left lower arm lower circum	

Clothing Item	size
T-shirt	
Zip t-shirt	
cotton gloves	
latex gloves	

u pad length = u arm length * 0 7 R= L=
u arm m circum = u pad length / 2 R= L=
l arm m circum = l arm length / 2 R= L=

PAD DIMENSION CALCULATION SHEET: ARMS AND ANKLES

_____

Subject

r ant/pos upper

height: upper arm height * 0.7

upper width: upper circum. / 2

mid width: mid circum. / 2

lower width: lower circum. / 2

r ant/pos lower

height: lower arm length
upper width: upper circum. / 2
mid width: mid circum. / 2
lower width: lower circum. / 2

l ant/pos upper
height: upper arm height * 0.7
upper width: upper circum. / 2
mid width: mid circum. / 2
lower width: lower circum. / 2

l ant/pos lower
height: lower arm length
upper width: upper circum. / 2
mid width: mid circum. / 2
lower width: lower circum. / 2

r lat ankle
height: lat ankle height * 0.6
width: ankle circum / 2

r med ankle
height: med ankle height * 0.6
width: ankle
circum / 2

l lat ankle
height: lat ankle height * 0.6
width: ankle circum / 2

l med ankle
height: med ankle height * 0.6
width: ankle
circum / 2

r/l glut
height: upper body length * 0.26
width: circum at ant. Sup. Iliac spine * 0.18

PLASTIC SHEETING CALCULATIONS: ARMS AND HANDS

Subject

Plastic Sheeting Calculations
r upper arm
height: (upper arm length * 0.7) + 5cm

upper width: (upper circum + 12) / 2

mid width: (mid circum. + 8) / 2

lower width: (lower circum. + 8) /2

r lower arm

height: lower arm length + 5cm

upper width: (upper circum + 12) / 2

mid width: (mid circum. + 8) / 2

lower width: (lower circum. + 8) / 2

l upper arm

height: (upper arm length * 0.7) + 5cm

upper width: (upper circum + 12) / 2

mid width: (mid circum. + 8) / 2

lower width: (lower circum. + 8) /2

l lower arm

height: lower arm length + 5cm

upper width: (upper circum + 12) / 2

mid width: (mid circum. + 8) / 2

lower width: (lower circum. + 8) / 2

Measurement Descriptions: Head, Face and Neck

Face

location	measurement description
Head height	Measured vertically from the bony tip of the chin to the top of the head
Head breadth	Measured horizontally across the head, above and behind the ears, where the head is broadest Hair is compressed
Forehead height	Measured from the upper margin of the eyebrow to the hairline, along the midsagittal plane
Cheek width	Measured from the outer (lateral) surface of the nostril to the the small projection of cartilage (tragus) found just in front of the external opening of the ear
Chin height	Measured from the bony tip of the chin to the lower margin of the lower lip, in the midsagittal plane
Jaw width	Measured horizontally between the outer angles of the mandible
Neck circumference	Measured around the neck, halfway between the Adam's apple and the top of the sternum The measurement should pass over the prominent vertebra (C7)
Neck height	Measured from the height of the Adam's apple to the sternum

Head

location	measurement description
Head length	Measured horizontally from between the brow ridges (glabella) and the most protruding part of the back of the head (occiput)
Anterior arc	Measured from ear to ear passing over the head at 1/3 the distance of the head length measured back from the hairline
Coronal arc	Measured from ear to ear over the crown of the head
Posterior arc	Measured from ear to ear passing over the head at 2/3 the distance of the head length measured back from the hairline

ABSORBENT PAD CALCULATIONS: HEAD, FACE, AND NECK

Subject _____

FACE

Forehead pad

Width: head breadth* 0.78

Height: eyebrows to hairline* 0.82

Cheek pads

Total width: distance between side of nose to ear* 0.75

Superior and inferior width: total pad width* 0.35

Medial height: head height* 0.21

Lateral height: head height* 0 42

Chin pad

Height: distance from bottom of lower lip to bottom of chin* 0.63

Width: Jaw width* 0.81

Neck Pads

Height: distance from Adam's apple to the sternum

Width: Neck circumference / 2

HEAD

Medial pads

Medial and lateral lengths - medial pads: med head length* 0.31

Anterior medial pad - anterior/posterior width: anterior arc* 0.33

Mid medial pad - anterior/posterior width: coronal arc* 0.32

Posterior medial pad - anterior/posterior width: posterior arc* 0.36

Lateral pads

Anterior lateral pad - total width: anterior arc* 0.31

Anterior lateral pad - anterior/posterior width: anterior lateral pad total width* 0.48

Anterior lateral pad - medial length: medial head length* 0.27

Anterior lateral pad - lateral length: anterior medial pad length* 0.32

Mid lateral pad - total width: coronal arc* 0.30

Mid lateral pad - anterior/posterior width: mid lateral pad total width*

0.48

Mid lateral pad - medial length: medial head length* 0.27

Mid lateral pad - lateral length: mid medial pad length* 0.32

Posterior lateral pad - total width: posterior arc* 0.34

Posterior lateral pad - anterior/posterior width: posterior lateral pad total width*

0.48

Posterior lateral pad - medial length: medial head length* 0.27

Posterior lateral pad - lateral length: posterior medial pad length* 0.32

Appendix C

Material testing

A series of tests were performed on the Tech Absorbents product 2164 and the 100% cotton sock and glove material to establish its stability and absorbency properties.

Material stability

A series of 2500 cm^2 control samples of Tech Absorbents product 2164, presented in Table 1, were weighed to establish the stability of the material and calculate the weight per surface area (g m^{-2}) The weight of the material appeared stable across samples, with an average of 181 ± 2.57 g m^{-2}.

Table 1. Absorbent material samples

Sample	Area (cm^2)	Weight (g)	Weight per SA (g m^{-2})
1	2500	45.48	181 92
2	2500	44.89	179.56
3	2500	45 85	183.40
4	2500	44 99	179 96
5	2500	46.31	185 24
6	2500	45 75	183.00
7	2500	44 03	176.12
8	2500	45.92	183 68
9	2500	44 24	176.96
10	2500	45 51	182.04
11	2500	44 78	179 12
12	2500	45 04	180.16
13	2500	45.30	181 20
14	2500	45 56	182.24
mean ± SD	2500 ± 0	45 26 ± 0 64	181 04 ± 2.57

Absorbency Testing

The absorbent properties of Tech Absorbents product 2164 and the 100% cotton glove and sock material were tested to ensure saturation would not be reached during sweat mapping trials. Samples of 100cm^2 product 2164 and 25 cm^2 material were weighed before being fully immersed in water for a 5 minute period This was sufficient to allow the material to reach saturation and to mimic the duration of the required test period for sweat mapping experiments The material was removed form the water and excess fluid allowed to drip off before being re-weighed. The weight change per surface area (g m^{-2})

was calculated for all samples (Table 2, Table 3, Table 4) The results indicate that 4655 ± 220 g m^{-2} of fluid can be absorbed by product 2164, 494 ± 82 g m^{-2} by the cotton glove material, and 696 ± 125 g m^{-2} by the cotton sock material. These values are in excess of the sweat rates indicated by current literature, suggesting that the material would not reach saturation during the present experimentation, particularly when considering the short measurement periods.

Table 2. Weight change of absorbent material calculated per surface area.

Sample	pre-test weight (g)	post-test weight (g)	Weight change (g)	Weight change per SA (g m^{-2})
1	1.90	49 82	47 92	4792
2	1 81	44.93	43.12	4312
3	1.82	47 82	46 00	4600
4	1 91	51 67	49 76	4976
5	1.88	50.30	48.42	4842
6	1 86	49.08	47.22	4722
7	1.78	45.20	43 42	4342
8	1 88	50.29	48 41	4841
9	1 80	46 94	45.14	4514
10	1 86	47.99	46 13	4613
mean ± SD	1 85 ± 0 04	48 40 ± 2 2	46.55 ± 2 2	4655 ± 220

Table 3. Weight change of cotton glove material per surface area.

Sample	pre-test weight (g)	post-test weight (g)	Weight change (g)	Weight change per SA (g m^{-2})
1	0.48	2 14	1.66	664
2	0.52	2 04	1 52	608
3	0.5	1 59	1 09	436
4	0 51	1 66	1.15	460
5	0.5	1 62	1.12	448
6	0 5	1 67	1.17	468
7	0 48	1.5	1 02	408
8	0 49	1.6	1.11	444
9	0.49	1 82	1.33	532
10	0.49	1 68	1.19	476
mean ± SD	0.50 ± 0 01	1 73 ± 0 2	1.24 ± 0 2	494 ± 82

Table 4. Weight change of cotton sock material per surface area

Sample	pre-test weight (g)	post-test weight (g)	Weight change (g)	Weight change per SA ($g.m^{-2}$)
1	0 63	2 69	2.06	824
2	0 60	2 38	1.78	712
3	0.58	1.98	1 40	560
4	0.58	2 22	1 64	656
5	0.58	1 97	1 39	556
6	0.58	2.09	1 51	604
7	0 68	2 47	1 79	716
8	0 68	2.87	2.19	876
9	0.65	2.83	2 18	872
10	0 64	2 11	1 47	588
mean ± SD	0 62 ± 0 04	2 36 ± 0.3	1.74 ± 0 3	696 ± 125