SWEAT MAPPING IN HUMANS AND APPLICATIONS FOR CLOTHING DESIGN

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INTRODUCTION

Regional Sweat Rate Measurement

Evaporation of sweat from the skin surface is the greatest avenue of heat loss from the body in warm and hot environments and during exercise. Dry heat losses via conduction, convection and radiation become limited in warm conditions when the temperature gradient between the environment and the skin is narrow. If environmental temperature exceeds skin temperature the body will gain heat via these mechanisms, resulting in complete reliance on evaporative heat loss. This is important in the regulation of core body temperature which becomes elevated in such conditions.

The majority of literature available on sweating concentrates on whole body sweat loss, with limited data available on regional sweat rates. Traditionally, whole body sweat rates are calculated from changes in body weight with adjustments for fluid intake, urine output, metabolic and respiratory losses. This approach is not suitable for measurement of regional sweat rates, with the development of more appropriate techniques such as ventilated capsules being readily used. Those that have measured regional sweat rates with such techniques have observed marked regional variation between the sites tested (Cotter et al. 1995; Hertzman 1957; Machado Moreira et al 2008a, b, c; Taylor et al 2006). These studies typically use a small number of sites with a limited surface area and make inferences to larger regions. Furthermore, although capsule techniques are useful for the constant and accurate measurement of sweat rates and onset, interference with the microclimate around the skin surface directly impacts the evaporative process (Nilsson 1977). Since sweating is related to the thermal state of the body, comparison of regional sweat rates between studies to obtain a global picture over the whole body is further complicated by the use of differing environmental conditions, exercise modes, work rates, and populations. To address this issue, a modified absorbent technique was developed to simultaneously measure regional sweat rates and distributions over a large number of sites across the body.

Body Mapping and Clothing Design

Clothing has a considerable impact upon heat exchange between the skin and the environment, typically hindering heat loss. This can significantly affect core temperature regulation when evaporative heat loss is compromised, particularly in clothing which has a high vapour resistance. Such conflicts between clothing function and thermoregulatory processes often occur with protective clothing. These conflicts can lead to discomfort and physical strain, which in extreme cases can lead to heat or cold related illness and injury. To maximise evaporative heat loss, calculations of regional ventilation requirements are necessary. Whole body sweat mapping techniques were developed to obtain detailed information on regional sweat rates and distributions which are required for such calculations. Sweat rate and onset are not uniform over the body, with regional variations widely recognized. Sweat production and the available cooling power are influenced by aerobic fitness, body composition, surface area-to-mass ratio, acclimation status, sex, age, clothing and evaporative efficiency (Candas et al. 1979; Havenith et al. 2008; Shapiro et al. 1982). By obtaining whole body sweat maps on a range of subject groups the opportunity arises for clothing designers to produce population specific clothing.

Although sweat mapping provides important physiological information for clothing design a further consideration is thermal comfort. Skin wettedness is recognised as a major factor in thermal comfort (Fanger, 1970; Havenith et al., 2002). It has been suggested that skin wettedness values in excess of 0.3, or a value related to metabolic rate, results in a loss of thermal comfort (Nishi and Gagge, 1970; Nishi and Gagge, 1977). It would therefore seem logical to maximise ventilation in regions of high sweat production to improve evaporative heat loss, minimise skin wettedness, and improve thermal comfort. However, it cannot be assumed that regional sensitivity to moisture mirrors regions of high sweat production. Fukazawa et al (2005) attempted to separate regional sensation from regional sweat rates using garments with areas of high and low permeability, affecting regional evaporation and therefore skin wittedness. The results indicated marked regional variation in skin wettedness sensitivity, with an inverse relationship between areas of high sweat rate (ie. central torso) and sensitivity. Clothing designers must therefore consider a complex integration of regional sweat rates, skin temperatures, and sensitivity for optimal heat loss and comfort.

METHODS

Experimental protocols were approved by the Loughborough University ethics committee and conformed to the guidelines set forth by the *Declaration of Helsinki*. Verbal and written consent were obtained from all subjects prior to participation. The sweat mapping protocol required subjects to undergo a sub-maximal fitness test, skin folds, and anthropometric measurements for the determination of absorbent pad dimensions in advance of the sweat mapping experiments.

Absorbent Pad Preparation: Two sets of absorbent pads were prepared in advance of each experiment; one for each exercise intensity. Each pad was weighed (Sartorius YACOILA, Sartorius AG, Göttingen, Germany) inside an individually labelled airtight bag. A total of 85 regions were measured on trained males, 70 on untrained males, and 78 on trained females.

All pads were individually sized to each participant. Regional sweat rates were calculated in grams per metre square of body surface area per hour ($g.m^{-2}.h^{-1}$) using the weight change of the pad, the pad surface area, and the length of time the pad was applied to the skin.

Experimental Protocol: A series of Caucasian subject groups were tested to compare regional sweat rates between sexes and differing aerobic fitness levels. To minimise the effect of the pads on the thermal state of the body, sweat mapping was separated into three experiments, each measuring approximately one third of the total surface area tested (1: upper body 2: legs 3: arms, hands, buttocks and feet). All subjects completed a 60 minute treadmill run involving two exercise intensities, each lasting 30 minutes (25°C, 50% rh, 2 $m.s^{-1}$ air velocity; work rates 55% and 75% VO_{2max} at 1% incline). Regional sweat rates were measured for 5 minutes at the end of each exercise intensity with the application of individually sized absorbent pads onto the skin surface. Pads were applied to custom made plastic sheeting for fast application to the skin and to prevent evaporation of sweat, and were held in place using a long-sleeved stretch zip t-shirt and trousers. Similarly, on the hands and feet 100% cotton gloves and socks were applied to the skin and covered with latex gloves or socks, respectively, to hold them in place and prevent evaporation. Infra-red images (Thermacam B2, FLIR Systems Ltd., Kent, UK) were taken at baseline, and prior to and following each pad application to measure skin temperature. Core temperature was monitored via a VitalSense Integrated Physiological Monitoring System (Mini Mitter Company, Inc. Bend, OR, USA) following ingestion of a CorTemp™ telemetry pill 5 hours before testing. Body weight was recorded at the beginning and end of testing and adjusted for fluid intake to calculate whole body sweat loss.

RESULTS

Figure 1 illustrates an example of body mapping of sweating in aerobically trained males modified from Smith and Havenith (2011). The sweat rates have been normalized to the area weighted median sweat rate of all regions measured. A value of 1 indicates a sweat rate equal to the median sweat rate of all regions. Values greater or less than 1 indicate sweat rates above or below the median sweat rate of all regions, respectively. Similarly to Figure 1, all subject groups tested showed marked regional variation in sweat rate and distribution at both exercise intensities. Although significant differences were present both within and between groups for the absolute quantity of sweat produced, regional patterns of distribution were consistent both within and between groups. The highest values were observed on the central and lower back, compared to the lowest values towards the extremities, in particular the hands and feet. No strong correlation was observed between regional sweat rate and regional skin temperature in any subject groups. Figure 2 illustrates the interpretation of body sweat maps by clothing designers for maximizing evaporative heat loss (sweat zones) in addition to skin temperature (heat zones) for consideration of dry heat losses.

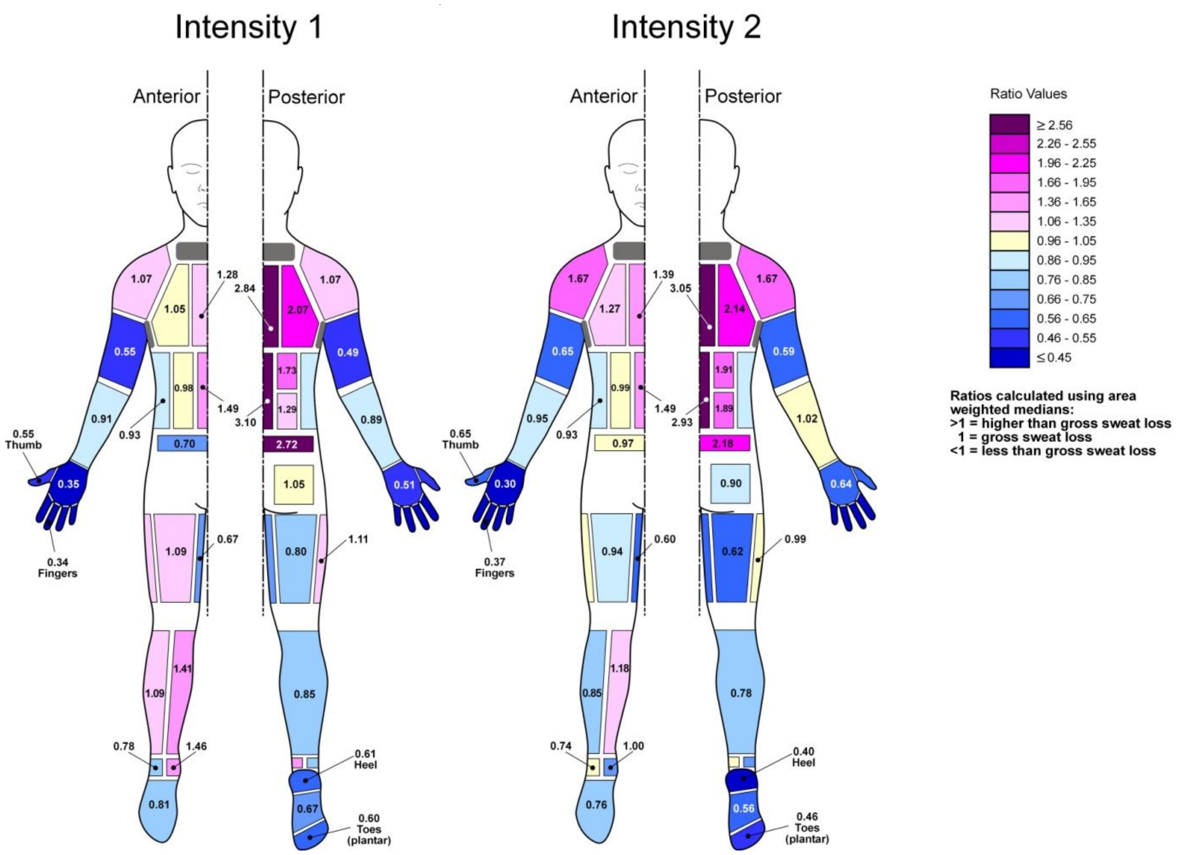

Figure 1. Normalised regional median sweat rates of male athletes at exercise intensity 1 and 2. The figures have been modified from Smith and Havenith (2011).

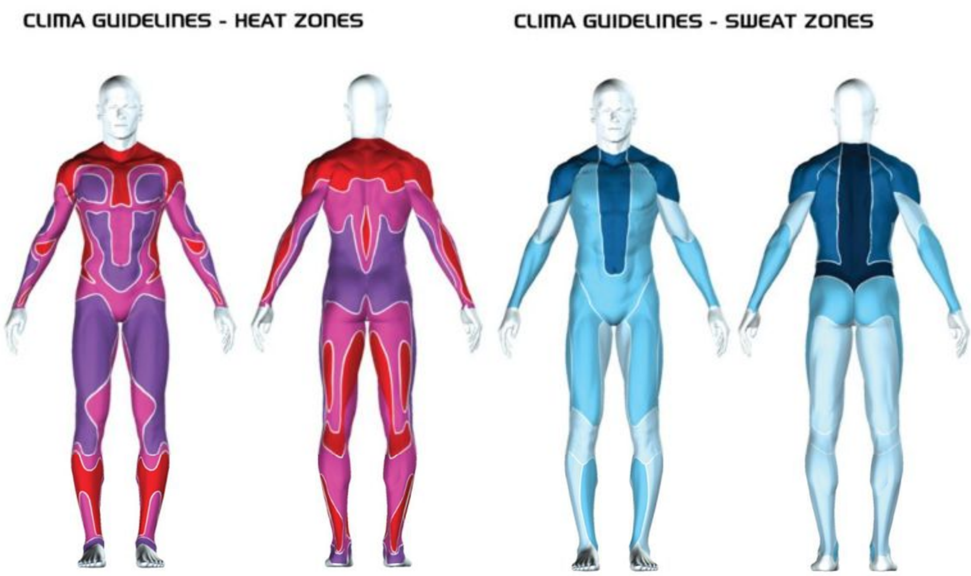

Figure 2. Regional temperature (left) and regional sweat (right) guidelines for clothing design based upon sweat mapping data (reproduced with permission from Adidas Innovation Team).

CONCLUSIONS

An understanding of thermal physiology, in particular the interactions of heat exchange between the skin, clothing and the environment are crucial in the design of clothing for optimizing temperature regulation, thermal comfort, and performance. Body mapping of sweating in humans provides the most detailed information currently available on regional sweat rates and distributions over large surface areas of the body. Previous research in this field has measured only a limited number of sites covering a small surface area of skin. The significant inter and intra-regional variation in sweat rate and distribution over the body observed in sweat mapping research provides a good opportunity for clothing designers to maximize heat loss and thermal comfort in the context of both sports clothing and protective clothing. Both dry and evaporative heat losses must be considered due to performance in different environmental conditions affecting mechanisms of heat loss. Despite no significant correlation between regional sweat rate and skin temperature, as observed by other authors (Cotter et al 1995), maintaining skin temperature within the comfort range (Fanger, 1970) is beneficial in improving thermal comfort. Figure 2 illustrates the 'heat zones' and 'sweat zones' which are targeted for maximizing dry and evaporative heat losses, respectively, in the design of Adidas Clima sport clothing. In particular, specific body regions may be targeted for the use of different fabrics and levels of ventilation to maximize evaporative heat loss from regions with high sweat rates, helping regulate core temperature, reduce skin wettedness, and improve thermal comfort.

Limitations

Body sweat mapping was performed across a variety of subject groups, however, these data are specific to each population. Furthermore, mild-exercise induced hyperthermia was used to elicit a sweating response and so generalization to other exercise modes or environmental conditions is limited. Secondly, any technique used to measure regional sweat rate will by its very nature affect the microclimate of the skin and therefore the variable that is being measured. This is true of the modified absorbent technique developed for sweat mapping due to the application of absorbent pads directly onto the skin surface. This may raise skin temperature, acting to artificially raise sweat rate in the regions being measured. Furthermore, the potential for moisture to become trapped on the skin surface, or for saturation of the absorbent pad, may result in a suppression of sweat rate. To minimize such interference the measurement periods were short in duration and a specific hygroscopic material was used for the absorbent pads, using less than 5% of its maximum absorption capacity.

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CONFLICT OF INTEREST

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