The Skin Interface - Meeting Point of Physiology and Clothing Science

George Havenith[1]*, Caroline Smith[1], Takako Fukazawa[2]

[1] *Loughborough University, Dept. Human sciences, Ashby Road, Loughborough, LE11 3TU, UK*
[2] *Fukuoka Women's University, Dept. of Living Environmental Sciences, Fukuoka-shi, Japan*

Abstract: This paper describes the relevance of knowledge of processes that happen at the skin for sports clothing design. It looks at skin temperature distribution while cooling, relevant e.g. to outdoor winter sports and mountaineering, at sweat distribution over the body while running, relevant e.g. to clothing designed for running in general and more particularly for exercise in warm and hot climates, and finally it looks into regional skin sensitivity, relevant for all fields of sports clothing design. As these areas interact heavily, the sports clothing designer needs to be aware of their influences and their interactions in order to optimise the clothing for the specific type of sport at hand.

Keywords: clothing, skin, comfort, sweating, evaporation, cooling

1. Introduction

A person at rest typically regulates their body temperature around 37°C, though this is by no means an exactly fixed temperature for all humans. Exercise will cause an increase in body temperature, which for many climatic conditions is unrelated to the temperature. Body temperature increases even with light to moderate exercise to values around 38°C, and up to 39 and occasionally above 40°C for heavy exercise (e.g. marathon) are

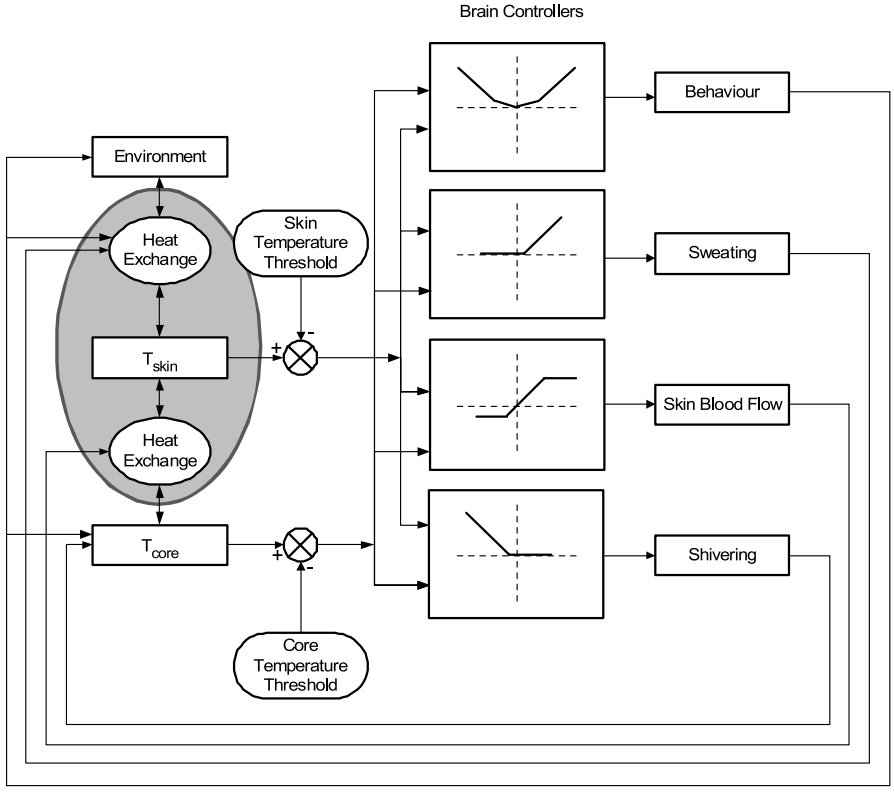

Figure 1, Schematic representation of the thermoregulatory control system. Tcore = body core temperature; Tskin = mean skin temperature; brain controller graphs show reaction of effector (Y-axes) to error signal (x-axes) (adapted from [3]). Grey area denotes the focus of present paper.

* Corresponding author's email: G.havenith@lboro.ac.uk

not uncommon, even in cool climates. Increases up to 39°C are seldom a problem to the body and should be considered a normal phenomenon in thermoregulation[1][2].

An example of how the body's temperature regulation could be represented is given in Figure 1 [3]. Here we have a body, which is represented by a body core temperature and by a skin temperature. Afferent signals representing these body temperatures are relayed to the control centres in the brain. There they are compared to a reference signal, which could be seen as a single thermostat setpoint, or as a number of thresholds for initiating effector responses. Based on the difference between actual temperature and the reference value (the error signal), various effector responses can be initiated.

For the present paper, the focus will be on the interface between the body and the environment: the skin (i.e. the grey area in Figure 1). Of the effector mechanisms, the internal ones are vasodilation of skin vessels (if body temperatures are higher than the reference, i.e. a positive error) and shivering and vasoconstriction (negative error). Shivering will increase heat production and heat the core, and vasodilation and constriction will regulate the heat transport between core and skin, and via skin temperature also the dry heat loss to the environment. The one that influences the exchange of heat externally (between skin and environment) most is sweat production. The evaporation of this sweat will cool the skin. Of course Figure 1 is a simplified model, as many different thermo-sensitive regions of the body have been identified, and other and more complex models are possible [3].

When we think of clothing we can think of it as an additional, behavioural effector response. Where possible we adjust our clothing levels to the climate we live in, providing the right amount of insulation to allow the other effector responses to stay within their utility range. The main effect of clothing will be its influence on the heat exchange between the skin and the environment. It will affect the heat loss of the body and will also impact the thermal sensation experienced by a person. Both are highly relevant to an individual's performance in sports.

Sports clothing can be worn for different reasons. In many sports protective clothing is worn, e.g. hockey gear protects against certain impacts. Clothing may also protect against the weather (mountaineering, skiing, sailing clothing). In many sports clothing is minimized however, in an attempt to limit any negative impact on heat loss and motion (e.g. running). These various applications all relate to heat exchanges at the skin, either limiting or promoting it. Hence a good understanding of what happens at this interface is important for optimal sports clothing design.

2. Thermal Insulation and Sports Performance - Cold Environments

For optimal sports performance the temperature of the muscles needs to be slightly raised. E.g. after warming the legs in a 44ºC water bath there was an increase of 11% in maximal peak force and power [4], which has been repeatedly shown for various muscle groups. Warm up, is considered beneficial [5][6] through temperature-related mechanisms (decreased stiffness, increased nerve-conduction rate, altered force-velocity relationship and increased lactic energy provision [5]), though other mechanisms have also been proposed. Only where warm up increases the overall heat load (warm up in warm and hot environments) negative effects are expected through its contribution to overall heat strain. Thus, for exercise in cool environments it is of the utmost importance to prevent excessive cooling of the body pre- and during exercise. This requires clothing to be adjusted in a way to prevent excessive heat loss. One option is to provide extra insulation overall, but a better solution may be found when this insulation can be targeted specifically at body regions with high heat loss.

When we think of cold protection, the initial thought goes to reduction of dry (radiative and convective) heat loss. This heat loss is defined by

$$Heat\ Loss = \frac{T_{skin} - T_{air}}{Insulation} \quad (1)$$

So, as air temperature is a given, it depends highly on skin temperature. If we want to target specific body areas for prevention of excessive cooling, we may thus be guided by the skin temperature profiles during such cooling. While a person is warm, especially with increased body temperature, skin temperatures will be rather uniform, due to the high blood perfusion of the vasodilated skin. Once a person starts to cool down however, vasoconstriction will occur and skin starts to cool down. Skin temperature will then be determined by the amount of heat that reaches the skin. This will be either via conduction via the tissues or via convective transport from body core to the skin by the remaining blood flow. Hence, areas with higher blood flow will be expected to be warmer, while, where blood flow is similar, areas with more tissue insulation (e.g. subcutaneous fat) tend to get a colder skin.

In order to analyse the skin cooling patterns an experiment was performed in which people with different body build were exposed semi-nude to a cool environment (12ºC, 50% rh, 2 m/s wind) while they were either passive, or while they were performing moderate exercise on a treadmill.

During this exposure, at regular intervals, skin temperatures were determined using Infra-Red thermography. Examples of results are given in Figure 2 These pictures illustrate nicely the effect of the sub-cutaneous fat distribution over the body, with the more obese person showing a dramatically cooler skin, while having a higher core temperature. Also the effect of the active leg muscles is evident.

The hot areas that remain are either linked to locations where major arterial blood flow comes close to the skin, dumping heat (e.g. neck) or to exercising muscles with little fat coverage (lower legs). The dark areas indicate cold skin and thus low heat loss after the initial cooling. For comfort, these should be targeted. The light areas on the other hand have remained warm and will continue to have a high heat loss and should be targeted if personal protection against hypothermia is most relevant.

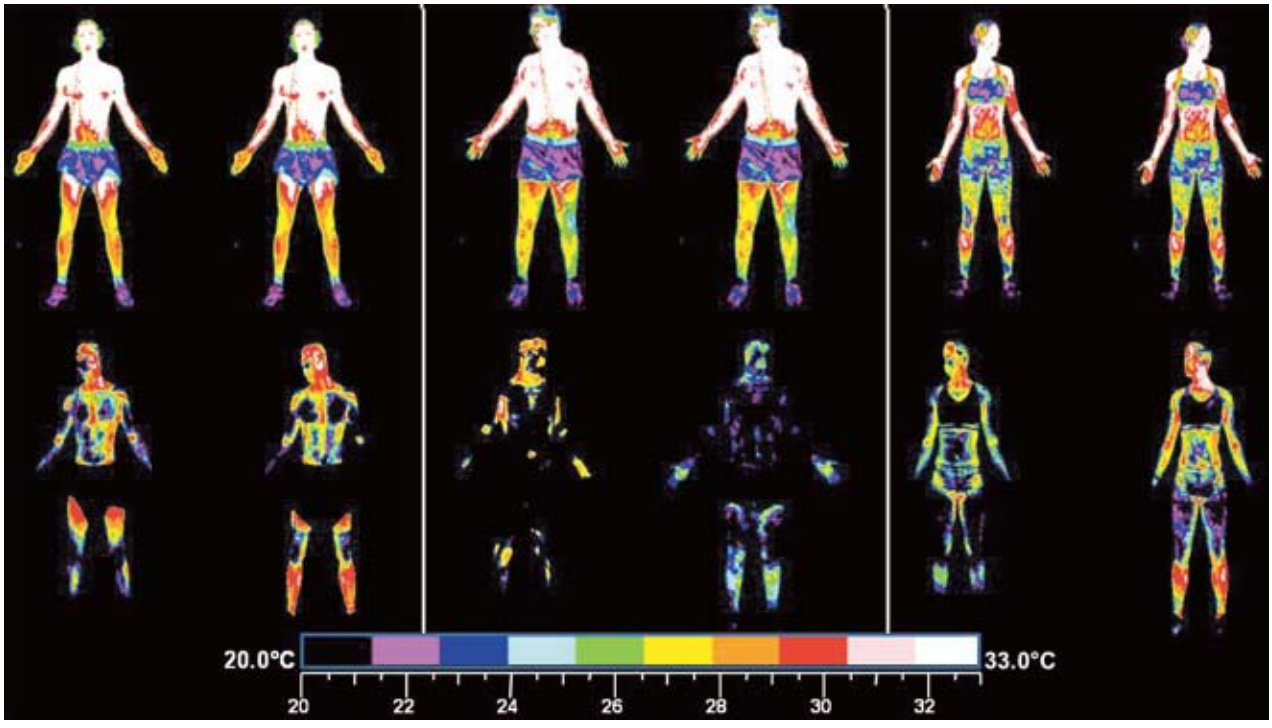

Figure 2 Thermograms of skin cooling patterns in three persons: Male lean, Male slightly obese, and Female. For each person: top pictures: before cooling in thermo-neutral state; bottom pictures: after 60 minutes of cooling in 12ºC, wind. Left: passive; right: active during cooling (walking)

3. Thermal Insulation and Sports Performance - Warm Environments

Many sports are performed in warm environments. E.g., the venue of the summer Olympics has been in warm climates for most of the recent games. This introduces two issues with clothing: Firstly high exercise intensities in general will produce heat stress, that requires optimal clothing design to reduce risks, and secondly, those needing to wear protective clothing will be very uncomfortable even at low exercise levels and due to the restrictions on heat loss posed by their protective clothing are even more at risk for hyperthermia. So in general there is a comfort issue and a heat stress issue.

Comfort is often seen as an irrelevant issue when top performance is discussed. However, experience from many other areas (e.g. military performance) has shown that discomfort has similar effects on performance as adding an extra task, thereby negatively affecting the personal performance. Hence, optimizing clothing in terms of comfort as well as performance are important goals for the clothing industry.

The most important features of clothing to be worn in warm or hot environment are:

- Minimising any negative effects on heat loss
- Maximising any positive effects on heat loss

Clothing will normally reduce heat loss due to its resistance to heat and to water vapour transfer. This negative effect can be reduced by selection of appropriate materials with low resistances, but mainly by the design. E.g. one important design feature is the introduction of air flows (ventilation) into the clothing. In order to do this optimally, it is important to identify which area of the body should be targeted in terms of heat transferred from the core to the surface (similar to section 2), and where the ventilation may be used maximally to remove (evaporate) sweat from the skin. The latter would require detailed knowledge of skin sweat patterns.

A positive effect of clothing on heat loss can be achieved by increasing the effect of evaporation efficiency. This again is related to ventilation, but can also be achieved by wicking of sweat from the skin into the textile which subsequently spreads the sweat over a larger surface from where it therefore can be evaporated at a higher rate. This effect is not so important when the athletes skin is fully wet all over the body, but wherever sweat distribution is unequal, the wicking of sweat may improve heat loss. Again, this requires knowledge of sweat distribution.

Sweat Mapping

Information on body sweat distribution is scant. Several groups have attempted to measure this, e.g. using small capsules that collect sweat in various places on the skin [8],[9], but this was always only for a very limited surface area [11]. Kuno [10] produced data on whole body sweat distribution on a small sample of Japanese people, though these data were mainly qualitative. Given the lack of whole body surface data, a need for more extensive studies of sweat mapping, measuring the whole skin surface was identified.

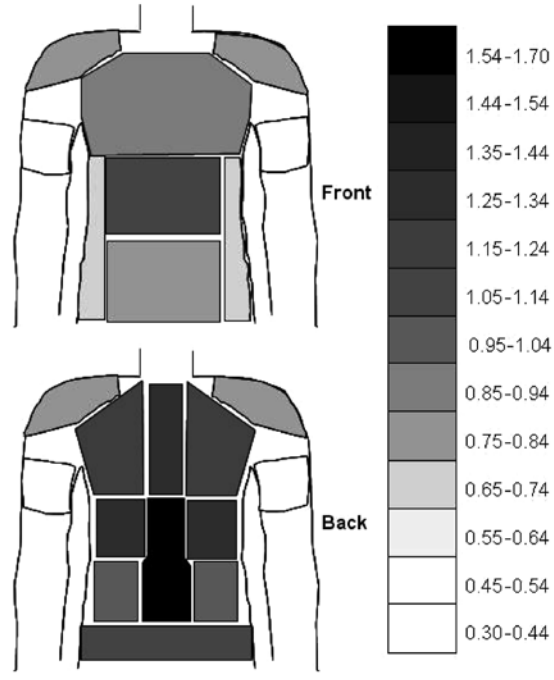

Figure 3 Sweat distribution patterns of male athletes in a 10 km run. Units express ratio of local to average sweat rate. Modified from [11]

Initiated by Havenith et al. [11], who studied regional sweat distribution on the torso, Smith et al. [12] (arms, hands) and Fogarty et al. [13] (feet) expanded this work with the goal to produce quantitative sweat maps covering the whole body

surface area. An example of such a sweat map for the torso is given in Figure 3 In this figure sweat rates on the torso are normalised to the mean sweat rate of all zones combined. Thus all values above 1 indicate higher than average sweating, values below one lower than average sweating. Figure 3 shows the quite dramatic variation in regional sweat rates over the torso, with peaks along the spine, and values reducing from medial to lateral areas. This mapping is currently extended to the whole body area, for males and females, pre- and post acclimatisation, for athletes of different fitness levels.

The observed variation on sweat production over the body implies excellent potential for regional optimisation of clothing design based on the sweat mapping. Using the body maps, designers can select materials with specific wicking properties and absorption capacities for different body parts. Also ventilation of the clothing can be influenced by design and the maps allow analysis of the optimal targeting of ventilation openings. The determined sweating patterns allow rather precise calculation of the required ventilation rates that need to be achieved to carry the produced moisture away from the body [14].

4. Comfort: Linking Sweating, Ventilation and Skin Sensitivity

The body temperature and sweating maps discussed in sections 2 and 3 provide valuable information on the physical status of the skin, and can be used by clothing designers and thermal modellers for their work. Though they help to select the most optimal target locations for interventions with special fabrics and designs, the maps on their own do not provide information on the thermal comfort provided by clothing. Comfort is very much linked to the temperature and the wettedness of the skin [15], but these both interact with the clothing worn. Furthermore, when talking about regional thermal comfort for different body areas, it is important to know the local sensitivity for temperature and skin wettedness in different body parts, as comfort will be determined by the levels of temperature and wettedness AND the skin sensitivity for these parameters (Figure 4). An area with low sensitivity may not require as much ventilation for example as an area with high sensitivity.

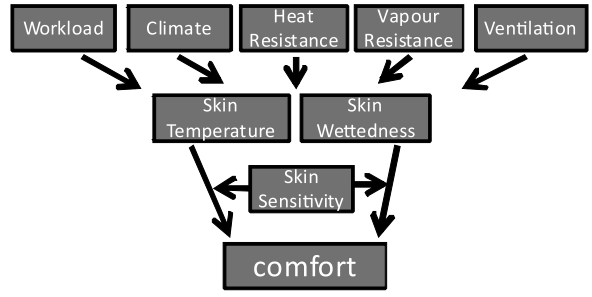

Figure 4, schematic representation of factors influencing thermal comfort.

Research on regional skin sensitivity is rather complex as there are many influencing factors. Fukazawa et al. [15] attempted to de-couple regional skin wettedness from regional sweat distribution by manipulating sweat evaporation from individual areas through specialised garments that were highly permeable in some areas and had low permeability in others. The highly permeable areas should allow sweat evaporation and produce low skin wettedness levels even for 'sweaty' areas, while the low permeability clothing areas should create high skin wettedness levels, even in areas with low sweat rate. Using different garments with the low permeability in different body areas, skin wettedness was manipulated as required to obtain the local skin sensitivity for this factor. Results (Figure 5) show a clear difference in sensitivity for skin wettedness,

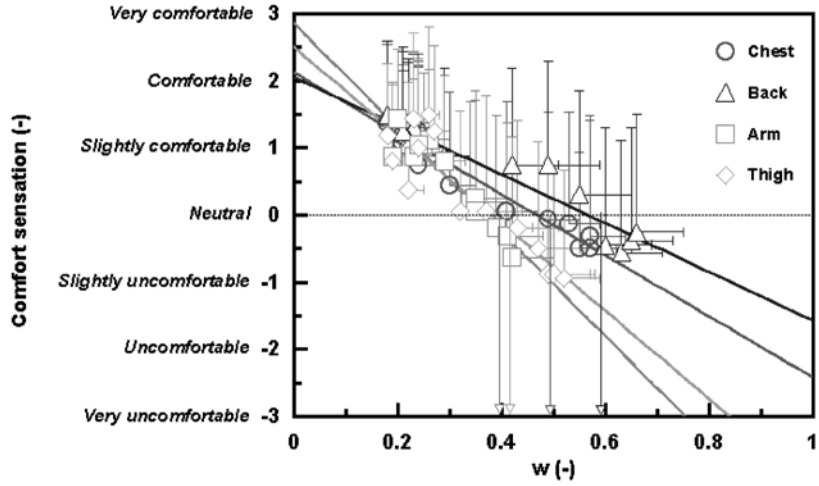

Figure 5, sensitivity of local comfort in relation to skin wettedness for chest, back, arm and thigh. Arrows to x-axis indicate the threshold for discomfort.

with central torso areas that normally exhibit a high sweat rate demonstrating a lower sensitivity than more peripheral areas that exhibit lower sweat production (Figure 3). It appears that sensitivity and sweat output show an inverse relation, and one may speculate that the product of sensitivity and production may be rather uniform over the body.

5. Conclusion

The various sections of this paper have shown how various aspects of skin 'behaviour' interact to provide a person with a sensation of thermal comfort, and how these aspects may inform clothing design. Knowledge of the regional properties of skin, be it in terms of cooling behaviour, sweat production, and skin sensitivity for comfort, allows the designer to optimise sports clothing for both performance and wear comfort.

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