From Textiles to Humans

The role of textile moisture transfer properties on human physiological and perceptual responses

by
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ABSTRACT

Clothing provides the body with a protective barrier from environmental factors, such as rain, snow, wind and solar radiation. Beside this imperative protective function, the interaction between clothing and the human body has implications in terms of temperature regulation and comfort. Specifically, wetness at the skin-clothing interface represents one of the highest sources of discomfort when wearing clothing, which could even contribute to reductions in human performance and, in extreme environments, impact human health.

To maximise heat and mass transfer through the clothing barrier, the textile and clothing industry constantly works on apparel innovations. Textile test methods allow assessments of objective improvements in material performance; however it is often unknown whether improvements at material level have an impact on human physiological and/or perceptual responses. Therefore, the aim of this research was to adopt an integrative paradigm in which textile and clothing moisture transfer parameters are instrumentally characterised and, subsequently, assessed in human physiological as well as sensorial experiments.

In this thesis, the current literature review focuses on the interactions occurring between the thermal environment, the human body and the clothes worn by the person (Chapter 1). The test methods applied to evaluate textile and clothing parameters are reviewed and discussed (Chapter 1). This is followed by an outlined of the methodological developments adopted in the current research to measure human responses when interacting with textiles and clothing, both during rest and exercise conditions (Chapter 2).

In the first laboratory study (Chapter 3), a skin regional experiment (fabrics applied on a restricted body area) was conducted to study the role of fabric thickness and fibre type on human cutaneous wetness perception, in condition of static fabric contact with the skin. In the same study, the approach adopted to characterise fabric moisture content, i.e. absolute (same μL of water per area (cm^2)) versus relative (same μL of water per unit of fabric volume (cm^3)) was studied and the

implications that fabric total saturation has on skin wetness perception were explored. The results showed the role of fabric thickness as major determinant of fabric absorption capacity and also wetness perception. In fabrics presenting same saturation percentage (same water content per volume) a positive relation between fabric thickness and wetness perception was observed and this was independent of fibre type. When applying the same relative to volume water content (same saturation percentage) thicker fabrics were perceived wetter than the thinner ones. Conversely, when applying the same absolute water amount, thicker fabrics were perceived dryer compared to thinner fabrics, given that thinner fabrics were more saturated. These findings indicate that human wetness perception responses between fabrics with different volume/thickness parameters should be interpreted in light of their saturation parameters rather than considering the absolute moisture content. In the same study, it was observed that the weight of the fabric in wet state can also modulate wetness-related perceptual responses. Specifically, 'heavier' fabrics were perceived wetter than 'lighter' ones, despite using the same fabric and applying the same level of physical moisture. This phenomenon was explained in light of the 'synthetic' nature of wetness perception, specifically through the effect of fabric weight on cutaneous perceived pressure which was associated with higher physical wetness in fabrics.

In a following skin regional experiment (inner forearm), the individual and combined role of fabric surface texture (contact points with the skin) and fabric thickness on wetness perception as well as stickiness sensation was studied (Chapter 4). In contrast to Study 1, in this experiment, fabrics were examined in dynamic contact conditions with the skin. It was observed that, when pre-wetted (same relative water content, corresponding to 50% of their maximum absorption capacity), fabric materials with a smoother surface (higher contact) resulted in greater skin wetness perception and stickiness sensation compared to the rougher fabric surfaces. Interestingly, the power of wetness perception prediction became stronger when including, together with stickiness, fabric thickness, indicating the important role of these two parameters when developing next to skin clothing. In the same dynamic application, to assess whether texture data can be used as predictors of fabric stickiness sensation, fabric surface texture was quantified using the Kawabata Evaluation System. The results showed that the Kawabata Evaluation System failed to predict stickiness sensation of wet fabrics commonly assumed to be associated with fabric texture, thus a different way to define fabric texture may be needed in order to represent this link (stickiness and texture).

Moving from this first research stage, where the impact of textile properties on human perceptual responses was investigated using a mechanistic approach, in the second research phase a more applied approach was adopted. The aim was to study textile parameters and clothing performance in conditions of exercise-induced sweat production as opposed to laboratory-induced wetness conditions.

Before investigating human sensorial responses in transient exercise conditions, in Study 3 (Chapter 5) we addressed potential biases which can occur when sensorial scores of temperature, wetness and discomfort are repeatedly reported in transient exercise conditions. We pointed out that, when repeatedly reported, previous sensorial scores can be set by the participants as reference values and the subsequent score may be given based on the previous point of reference, the latter phenomenon leading to a bias which we defined as 'anchoring bias'. Indeed, the findings showed that subsequent sensorial scores are prone to anchoring biases and that the bias consists in a systematically higher magnitude of sensation expressed, as compared to when reported a single time only. As such, the study allowed recognition and mitigation of the identified error, in order to improve the methodological rigour of the following research involving sensorial data in transient exercise conditions.

Following from Study 2, where the impact of stickiness sensation on wetness perception was highlighted, in the fourth laboratory study (Chapter 6) we aimed to investigate the combined effect of garment contact area, sweat content and moisture saturation percentage, in conditions of exercise-induced sweat production. Furthermore, the influence that both stickiness sensation and wetness perception have on wear discomfort was studied. The findings showed that fabric saturation percentage mainly affected stickiness sensation of wet fabrics, dominating the impact of fabric contact area and absolute sweat content. On the contrary, wetness perception was not different between garments. This indicated that stickiness sensation and wetness perception are not always strongly related; as such they should both be measured and considered individually. Texture and stickiness sensation presented the best relation with wear discomfort at baseline and during exercise, respectively.

Due to the impact of fabric moisture saturation percentage on stickiness sensation and wear discomfort, identified in Study 1 and Study 2, in Study 5 (Chapter 7) we aimed to quantifying temporal and regional sweat absorption in cotton and synthetic upper body garments. Sweat production was induced in male athletes during 50 minutes of running exercise, performed in a warm environment. Considerable variations in sweat absorption were observed over time and between garment regions. Based on these data, we provided temporal and spatial sweat absorption maps which could guide the process of clothing development, using a sweat mapping approach.

In Study 5 a 'destructive' gravimetric method was developed to quantify local garment sweat absorption. While this currently is the only methodology that permits direct and analytical measurements of garment regional sweat absorption, the latter approach is time-consuming and expensive, therefore of limited applicability. As such, in study 6 (Chapter 8), it was assessed whether infrared thermography could be used as an indirect method to estimate garment regional sweat absorption, right after exercise, in a 'non-destructive' fashion. Spatial and temporal sweat absorption data, obtained from Study 5, were correlated with spatial and temporal temperature data (also obtained from study 5) measured with an infrared thermal camera. The data suggested that infrared thermography is a good tool to qualitatively predict regional sweat absorption in garments at separate individual time points; however temporal and quantitative changes are not predicted well, due to a moisture threshold causing a temperature limit above which variations in sweat content cannot be discriminated by temperature changes any further.

In conclusion, the textile parameters identified in this PhD research as major determinants of fabric absorption capacity and related perceptions are thickness/volume, 'wet' weight, moisture saturation percentage, surface area and surface texture. These textile factors influence wetness-related sensations and perceptions over time, in relation to the over-time changes in human thermophysiological responses (such as metabolic rate and sweating) and to the environmental conditions the person is exposed to. This clearly shows that in a multifactorial system such as the environment-human-clothing one, the strength of different cutaneous moisture-related stimuli, triggered by various textiles parameters, should be considered. Finally, this indicates that, to obtain a better understanding of clothing performance and its impact on human sensations, human assessments should be conducted using a holistic approach, i.e. different wetting procedure (relative and absolute water amount) and wetness-induced scenarios (laboratory- and sweat-induced) involving mechanistic as well as applied research approaches (skin regional and whole body studies).

STATEMENT

The work presented in this thesis was co-funded by the Environmental Ergonomics Research Centre, Loughborough Design School, Loughborough University, and adidas FUTURE Sport Science Team. This thesis represents the original work of the author. The use of the word ‘we’ throughout this thesis is to acknowledge the contribution of other people to the current research work.

Due to the size and complexity of the research methodology and the number of experiments necessary to answer the identified research questions, two BSc dissertation students, Mr Kolby Pistak and Mr Benjamin Sales supported the data collection of Study 2 and Study 3, respectively. The author designed the experiments and, for inclusion in this thesis, all such experimental data were analysed and interpreted by the author only. Dr Christian Heyde, as industrial advisor, supervised the experimental design of Study 3, Study 4, Study 5 and Study 6. Dr Alex Lloyd provided support for the data collection of Study 5. Dr Jianguo Qu performed the measurements of fabric surface texture using the Kawabata Evaluation system (Study 2). Prof George Havenith and Dr Simon Hodder supervised the development of the experiment design, data analysis and discussion of the results of all the experimental studies reported here.

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PUBLICATIONS

JOURNAL PAPERS

Raccuglia M, Heyde C, Lloyd A, Hodder S, Havenith G, (2017) Anchoring biases affect repeated scores of thermal, moisture, tactile and comfort sensations in transient conditions. International Journal of Biometeorology *(accepted with minor corrections)*.

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AWARDS & INVITED TALKS

AWARDS

2018 Santander Mobility Award – Loughborough University, Doctoral College

Competitive travel fund awarded to support a visit to an overseas institution. The fund was utilized to promote activities that improve research collaborations and/or networks between Loughborough University and The Research Centre in Sports Sciences, Health Sciences and Human Development - CIDESD-ISMAI, in Porto, Portugal.

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Competitive prize awarded for 2nd best oral presentation at The International Conference of Environmental Ergonomics, ICEE (Nov 12-17, 2017, Kobe, Japan).

2017 Travel Fund – Loughborough Graduate School

Competitive travel fund awarded to support the attendance of the annual meeting of the American College of Sport Medicine (May 30 - June 3, 2017, Denver, Colorado, USA).

2017 Design School Research Student Conference (DesRes)

Competitive prize awarded for best oral presentation.

2016 Travel Fund – Loughborough Graduate School

Competitive travel fund awarded to support the attendance of the Experimental Biology Conference (Apr 2-6, 2016, San Diego, California, USA).

2016 PhD exchange fund – Loughborough Graduate School

Travel fund awarded to support a period of two weeks visit to the Noll Lab, Penn State University. The aims of the visit were to learn some invasive techniques to study local thermoregulatory responses, such as microdialysis, microneurography, skin biopsy and to create the basis for future collaborative research projects between Loughborough University and Pen State University.

2015 Summer Showcase – Loughborough Graduate School

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INVITED TALKS

Raccuglia M, Havenith G, (2017) Wetness sensation during rest and exercise and the interaction with textiles: how can you feel it? The 17th *International Conference on Environmental Ergonomics 12-17 November 2017.* Kobe, Japan.

Raccuglia M, Hodder S, Havenith G, (2017) Human wetness perception: from skin to clothing. *64th American College of Sport Medicine 1st June 2017*. Denver, Colorado, USA

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CHAPTER 1

Critical review of the literature

1.1 Review introduction

1.1.1 Overview and method

In the current literature review highlighted are the implications that clothing has on human thermoregulatory responses, temperature, moisture and comfort sensations. In this regard, included is a critical appraisal of the physical avenues for body heat transfer, the human thermoregulatory system, as well as the sensory mechanisms underlying cutaneous temperature and moisture sensations. Furthermore, the methods used to evaluate textile thermal and moisture properties are summarised and discussed. Finally, this review proposes a human-orientated evaluation process for the development and assessment of functional clothing.

The published, peer-reviewed journal papers used in this critical review were sourced from online journal search engines including Google Scholar, Web of Science, PubMed, Science Direct and Scopus. Journal articles were included based on a critical assessment of methodological validity.

1.1.2 Introduction to the research topic

The challenge for every person is to successfully interact with his or her thermal environment (Parsons 2014). The thermal environmental determines human thermal responses which are aimed to achieve thermal balance. Clothing is an essential part of human life which modulates the dynamic interaction between the human body and the surrounding thermal environment. Specifically, clothing affects heat and mass transfer along with eliciting human sensory responses, including haptic, thermal and moisture sensations. The interactions between the various components of the environment-human-clothing system substantially impact the performance of clothing and determine the thermal and comfort state of an individual.

The multifactorial nature of the environment-human-clothing system explains our inability to characterised clothing performance simply using instrumental material and clothing test methods. Material tests often involve the application of a single environmental condition, which may be insufficient as, for many other applications, different temperatures, humidity levels or air flow levels are relevant. Additionally, material testing neglects the contribution of personal factors, such as body shapes, posture and work intensity, on the end-performance of clothing. This does not mean that textile test methods cannot provide useful information with regards to fabric and clothing properties. Nonetheless, this suggests that material testing represents only a single part of the clothing evaluation process and that final conclusions regarding clothing performance require additional evidence that can only be provided by human assessments.

1.2 The environment- human- clothing system

The thermal environment is characterised by four basic parameters: air temperature, radiant temperature, humidity and air movement. When combined with the metabolic heat produced by the individual during physical work and with the clothes worn, they provide six fundamental factors traditionally defined by Fanger (1970) as the human-thermal environment. Nevertheless, given the critical contribution of clothing factors, it seems more appropriate to define this as the environment-human-clothing system. The human body responds to the continuous changes of this system by regulating body core temperature within a temperature range which is compatible with the human life, this being around 37 ^{o}C. This value is obtained by achieving a dynamic equilibrium between heat produced and heat loss to the environment.

1.3 The thermal environment

1.3.1 Heat balance

The avenues for heat transfer from the body to the environment and vice versa are conduction, convection, radiation and evaporation. Conductive heat transfer is relevant only for people working in water, in special gas mixtures, handling cold products or in supine and sitting position (Havenith 1999). Conductive heat transfer can also occur when the body is in contact with wet clothing, based on the amount of liquid content and the heat capacity of the wet material to extract heat from the skin in contact with it. Nevertheless, it is important to carefully consider this avenue, as conductive heat transfer with wet clothing can occur in concomitance with evaporative heat transfer both from the wet clothing and skin. Convection is a more important pathway and it occurs when the air flows through the skin. If the temperature of the air is colder than the skin heat will be transferred from the skin to the environment and vice versa if air temperature is warmer. Heat transfer through convention, as result of a temperature gradient, is defined natural convection. On the other hand, heat transfer through forced convection commonly occurs in presence of wind. At the lungs, convective heat transfer occurs when the cool air from the environment is inhaled and heated to the body core temperature. By warming and moisturising the inspired air, the body loses an amount of heat which can be up to 10% of the total heat production (Havenith 1999). Electro-magnetic radiation is another pathway for heat transfer. Heat transfer via radiation occurs when there is a difference between the body surface temperature and the temperature of the surfaces present in the environment. Finally, the human body possesses the ability to dissipate a large amount of heat through evaporation of sweat (described later in this thesis). The processes of heat production and heat loss are conceptually described by the heat balance equation (Parsons 2014):

$$M - W = E + R + C + K + S$$

Where:

M *metabolic rate;*

W *external work*

E *evaporation*

R *radiation*

C *convection*

K *conduction*

S *heat storage*

1.3.2. Basic parameters

The thermal environment is characterised by a number of parameters that strongly influence the capacity of the body to lose or retain heat. These include air temperature, radiant temperature, surface temperature, air velocity and air humidity.

In high air temperatures (T_a), less heat can be lost from the body through convection and radiation. If T_a is higher than body skin temperature (T_{sk}), the body will gain heat from the environment and both T_{sk} and body core temperature (T_{core})

will rise. Convective heat loss from the skin is affected by the temperature gradient between the skin surface and the surrounding environment and by the presence of air movement, which affects the convective heat transfer coefficient (h_c, $W \cdot m^{-2} \cdot {}^{o}C^{-1}$). The magnitude of air movement ($m \cdot s^{-1}$) affects both convective and evaporative heat loss. High air movement (~ > 0.2 $m \cdot s^{-1}$) causes the removal of the boundary air layer surrounding the skin and convective heat loss increases. Because of the dependence of convective heat loss upon the gradient between T_{sk} and T_a, cooler air will increase the rate of convective heat loss whereas warmer air will reduce it or even result in heat gain at higher temperatures. In conditions of very high wind speed, sweat can be very quickly removed from the skin surface as liquid and before heat from the skin can be removed, which is not desirable for an efficient body heat loss.

The driving force for sweat evaporation from the skin surface is the partial water vapour pressure gradient between the skin (P_{sk}) and the environment (P_a). When moisture concentration at the skin is higher than in the environment, evaporative heat loss from the skin surface will occur. On the other hand, as the partial water vapour pressure gradient between the skin and the environment decreases, the potential amount of evaporation will be reduced. It is important to point out that moisture concentration, rather than relative humidity is the determining factor for this avenue. In fact, air that has a relative humidity of 100% can contain different amounts of moisture, depending on its temperature (Havenith 1999). The higher the temperature, the higher the moisture content at equal relative humidity. When air temperature is lower than skin temperature, sweat will always be able to evaporate from the skin surface, even at 100% relative humidity. In hot-dry environment heat loss via evaporation of sweat can account for as much as 85-90% during exercise (Armstrong 2000).

Radiant temperature can be considered as the mean temperature of all the walls and objects in the surrounding space where the person is placed. It determines the extent to which radiant heat is exchanged between the skin and the environment. For people working in sunny outdoor conditions, radiant temperature can easily exceed skin temperature, resulting in radiant heat transfer from the environment to the skin (Havenith 2002).

Finally, the temperature of the surfaces in contact with the body determines conductive heat transfer. Beside temperature of the surfaces, other factors affecting conductive heat transfer are thermal conductivity and heat capacity (Havenith 1999).

1.4 The human body

The environment-human-clothing system is a dynamic organisation in which the interaction between its numerous factors causes the initiation of human thermal responses and impacts the way in which clothing performs. Despite the dynamic nature of this system, the only component that can be defined as 'active' is the human body, in that it can dynamically respond to changes in the thermal environment and clothing performance. Conversely, the thermal environment (especially outdoor environments) and clothing (apart from effectively working 'smart' clothing) do not actively adjust to assist body thermal balance and comfort. Thus, the thermal environment and the clothing can be considered as 'passive' components of the system.

Following are described the mechanisms through which the human body can react to thermal changes in the system. Additionally, the cutaneous sensory modalities through which the human body can gain information regarding the surrounding environment will be discussed. Finally, since wetness in the skin-clothing system is one of the main factors affecting thermal balance and wear comfort, the topic of human body sweating will be examined in details.

1.4.1 Thermoregulation

Body heat production is determined by metabolic activity. At rest, metabolic activity occurs when the body cells are provided with oxygen and nutrients to maintain body's basic functions, for instance, respiration and heart function. On the other hand, during physical work the need of the active muscle cells for oxygen and nutrients increases, resulting in a higher metabolic activity. When the muscles burn nutrients and oxygen for mechanical work, part of the energy is released to the environment as external work but most of it is liberated in the muscle as heat. The ratio between external work and the energy used is the efficiency of the work performed. The human body responds to the changes in body metabolic heat production and thermal environment (Parsons 2014) through autonomic and behavioural thermoregulatory mechanisms.

Under normal conditions, body temperature is maintained at a certain level by the vasomotor responses activated by skin temperature, or by thermal stimuli from the surrounding environment (Mekjavic and Eiken 2006) (Fig 1). Vasomotor responses include vasodilatation and vasoconstriction. Vasodilatation causes blood flow to be radiated from the core to the periphery (skin) and during this process heat is transferred via conduction, convection and radiation from the deeper body regions to the skin. Vasoconstriction causes reductions in skin blood flow to keep the warmer blood near the core and the vital organs. The range of ambient temperatures, in which the responses of metabolic heat production and evaporative heat loss are absent, and the maintenance of body temperature is solely achieved by vasomotor responses, is defined as the thermoneutral zone (TNZ, Fig 1) (Mekjavic and Eiken 2006). In humans, the TNZ has been observed to range from 33 to 35°C (Savage and Brengelmann 1996). In Figure 1, the dashed lines indicate how non-thermal factors may affect the vasomotor responses (Romanovsky et al. 2002) and, by doing so, also the magnitude of the TNZ.

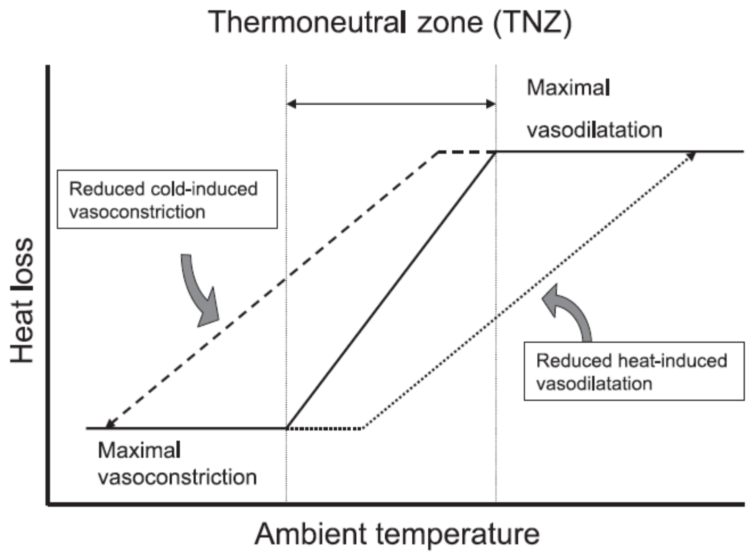

Figure 1 Schematic representation of the thermoneutral zone (TNZ) from Mekjavic and Eiken (2006).

Once the capacity of the vasomotor response to maintain a stable core temperature (T_{core}) is exceeded, the appropriate autonomic responses of sweating or shivering are activated. The T_{core} at which these effectors are initiated is defined as the thermoeffector threshold T_{core} (Fig 2). The concept of a range (zone) of T_{core}, which, similar to TNZ, induces neither heat production nor heat loss change can be observed (Mekjavic and Eiken 2006). Specifically, this T_{core} zone is bounded by the thermoeffector threshold temperatures for sweating and shivering, and is defined as interthreshold zone (Fig 2). Sweating thermoregulatory responses occur when body heat loss increase is required. In details, the sweat glands are stimulated to initiate and/or increase sweat production and thus heat loss through evaporation. Evaporation of sweat requires energy (heat) which is taken from the skin, causing cooling of the skin as well as of the blood close to it. The cooled blood will then flow back to the core to lower body T_{core}. Evaporation of sweat is the most dominant avenue of heat loss during exercise (Kerslake 1972). Sweat rates of up to 1 lhr^{-1} have been reported when exercising in the heat (Brake and Bates 2003). Shivering is a mechanism initiated when T_{core} is reduced, i.e. in cold conditions. Shivering increases metabolic heat production via voluntary or involuntary small and rapid muscle contractions. Together with shivering, piloerection is another mechanism to reduce body heat loss. This mechanism involves tiny muscle contractions which cause the hair on the body surface to stand at the end. Through piloerection, heat loss is reduces as this process maintains a layer of still air between the body and the environment, alongside increasing metabolic rate (Parsons 2014).

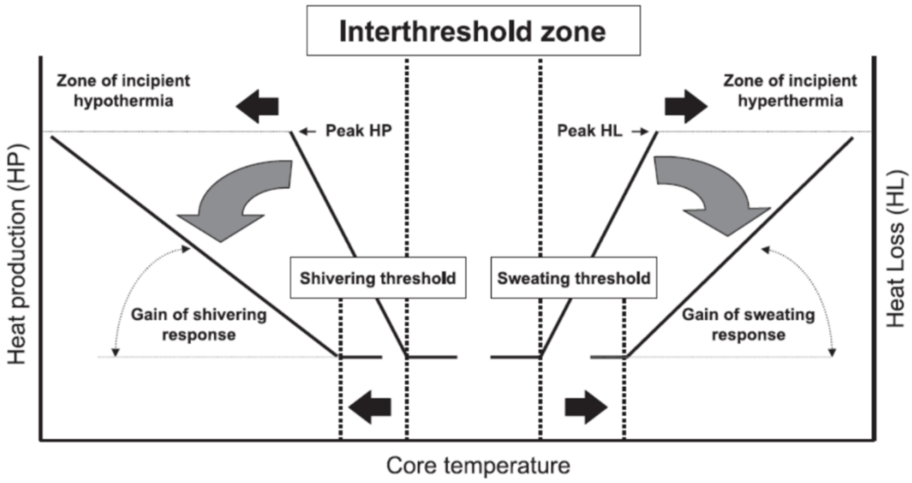

Figure 2 Schematic representation of the interthreshold zone, or thermoeffector threshold zone from Mekjavic and Eiken (2006).

According to the above-described model of body thermoregulation, sweating and shivering do not need to be initiated as soon as changes T_{core} are sensed. This instead would be the case of a set-point regulation model. In the set-point model of temperature regulation, deep body temperature (T_{core}) is compared with a reference temperature (37 ^{o}C), resulting in a temperature error signal, which then evokes appropriate thermoeffector responses. Reductions or elevations in deep body temperature are detected by the thermoreceptors, located at the periphery (skin) and central locations (brain, spinal cord and viscera) in the human body (Nakamura, 2011; Schepers & Ringkamp, 2010). The central controller of temperature regulation, located in the pre-optic area of the hypothalamus (anterior portion of the hypothalamus) (Romanovsky 2007), attempts to minimize the error signal, thereby ensuring regulation of deep body temperature at a set-point. A control system model may be a simple and convenient analogy to explain how deep body temperature is regulated in mammals (Hammel and Pierce 1968). However, it is questionable whether such kind of regulation of physiological systems exists in reality.

In the model developed by Havenith (2001a), it can be observed that, beside environmental parameters (heat transfer properties) and heat production levels (activity), the relation between thermoregulatory effectors and resulting body temperature is also affected by individual parameters of body mass (m), body fat layer thickness, body surface area (AD), VO_{2max} and acclimation state (Fig 3). In this model, core, skin, and mean body temperatures are used as input for several set-point defined feedback loops controlling effector responses (skin vasoconstriction/dilation, sweat production, shivering). The effector responses together with metabolic heat production (basal + work) result in a certain heat loss or gain, which then affects the 'passive' system (the body), resulting in a new body temperature (i.e. the feedback).

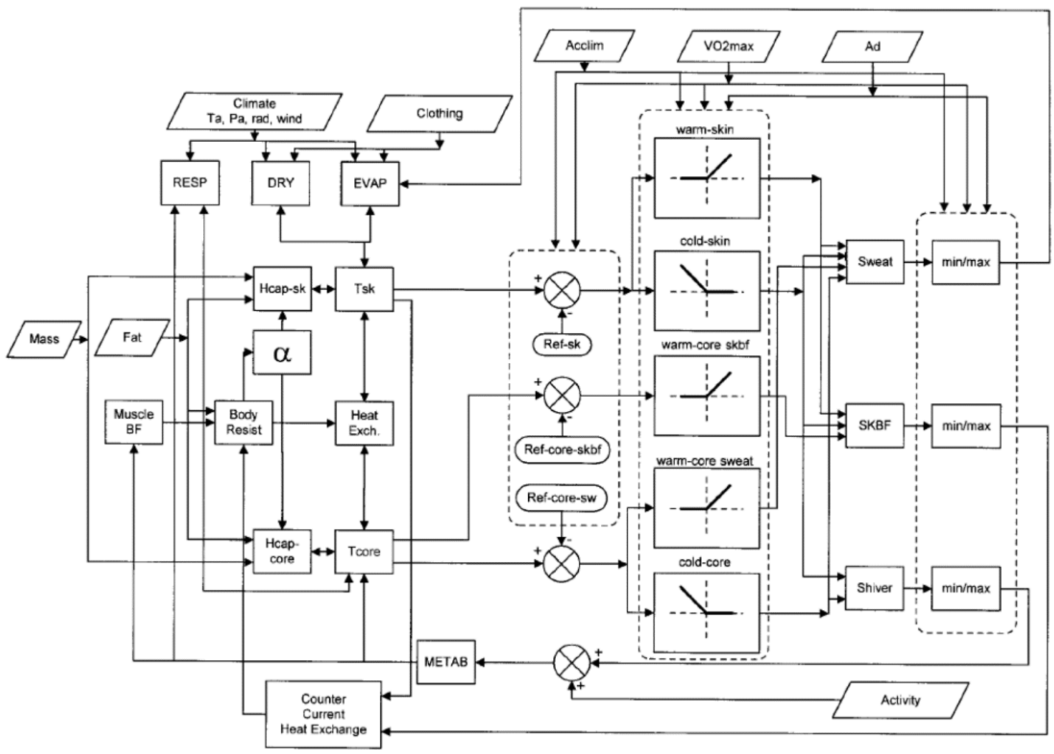

Figure 3 Schematic representation of the physiological control system. The model includes, the inputs [climate, clothing, activity, mass, fat content, acclimation (Acclim), maximal O2 consumption (V˙ O2max), and body surface area (AD)] and the heat exchanges between body core and environment from Havenith (2001a).

The autonomic thermal mechanisms are of vital importance; however, these responses are less effective in ensuring thermal balance and human survival when the body is exposed to extreme thermal environments. Physiological and biophysical factors, in fact, can limit the functional capacity of the autonomic thermoregulatory system (Schlader et al., 2010). For instance, maximal sweating, maximal vasoconstriction, as well as vasodilation are limited by physiological (e.g. sweat glands density and output, number of capillaries) and biological factors (e.g. age) (Kenney and Munce 2003). Additionally, anthropometric parameters play a role in limiting the efficiency of the autonomic thermoregulatory system. In fact, heat losses are proportional to the surface area available for heat exchange (Havenith 2001b).

To compensate the limitations of the autonomic thermoregulatory system, the human body responds to the changing thermal environment through behavioural adjustments, for instance donning or taking-off clothing, changing posture, moving to the shadow or to a source of heat (Flouris 2011). In this respect, behavioural responses represent the most powerful thermoregulatory effectors.

1.4.2 Thermal sensitivity

The main driving force that allows the initiation of behavioural as well as autonomic thermal responses is the human ability to sense the thermal properties of the surrounding environment (Spray 1986) and of one’s own body (Craig, 2003). This ability is defined as thermal sensitivity and is given by the presence of thermoreceptors, located peripherally (skin) and centrally (brain, spinal cord, muscles viscera) within the body. Once the thermoreceptors are elicited by external stimuli, their role is to provide the central nervous system with afferent information regarding the thermal properties of the environment (Schepers and Ringkamp 2010). The integration of these thermal afferent feedback will then results in the initiation of autonomic thermal response (Kondo et al. 1997; Morris et al. 2014) as well as behavioural ones (Schlader et al. 2013) in an attempt to maintain thermal balance and comfort (Cabanac et al., 1972; Schlader et al., 2010).

1.4.3 The skin

The skin is one of the means through which the human body can obtain information regarding the surrounding thermal environment. When considering the clothed human body, the interaction between the skin and the environment is mediated by clothing parameters.

1.4.3.1 Anatomy of the skin

The skin is the largest organ of the human body. In an adult, the skin covers a surface area of 1.6-2 m^2 and has a weight of approximately 5 Kg (Myles and Binseel 2007; Derler and Gerhardt 2011). It is a membrane composed of a superficial epithelium defined epidermis and the underlying connective tissues of the dermis (Fig 4). Beneath the dermis, the loose connective tissue of the hypodermis (or subcutaneous layer) attaches the skin to the deeper structures such as muscles and bones (Martini et al. 2013).

The epidermis consists of stratified squamous epithelium divided into different layers. In order from the basement membrane toward the free surface, these layers include stratum germinativum, an intermediate stratum (stratum spinosum, stratum granulosum and stratum lucidum) and finally the stratum corneum (Martini et al. 2013). The stratum germinutivum is the deepest epidermal layer and is attached to the basement membrane that separates the epidermis from the dermis. The stratum germinativum is dominated by stem cells; in this layer new cells are generated and begin to grow. The cells from the basal layer are displaced in the intermediate stratum, from spinosum to granulosum and finally to lucidum, and during the transfer across layers the cells become specialised to form the outer protective layer of the skin. The most superficial layer is represented by the stratum corneum, consisting of 15-30 layers of death epithelial cells.

The dermis (Fig 5) lies beneath the epidermis and consists of the papillary layer, characterised by connective tissue which supports the epidermis, and the reticular layer consisting of elastic and collagen fibres to provide flexibility and stability at the same time and prevent skin injuries (Martini et al. 2013). Epidermal accessory organs, such as hair follicles and sweat glands, expand into the dermis (Fig 5). The dermis also contains other components such as lymph vessels, blood vessels and nerve fibres (Fig 5).

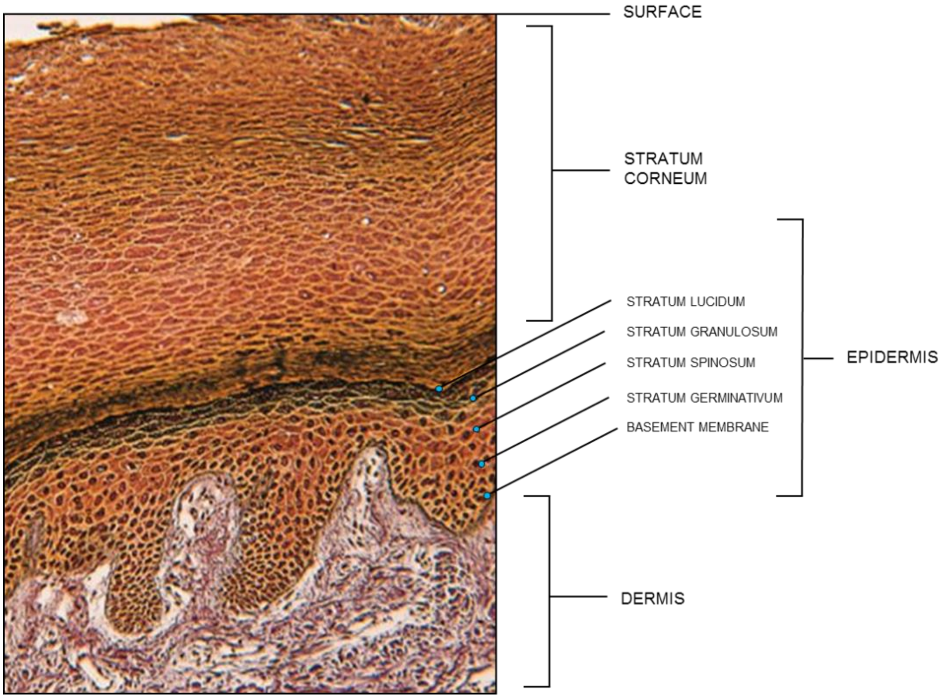

Figure 4 The structure of the skin, including epidermis and dermis. Specifically, the section of the epidermis in thick skin shows all five epidermal layers. From Martini et al. 2013.

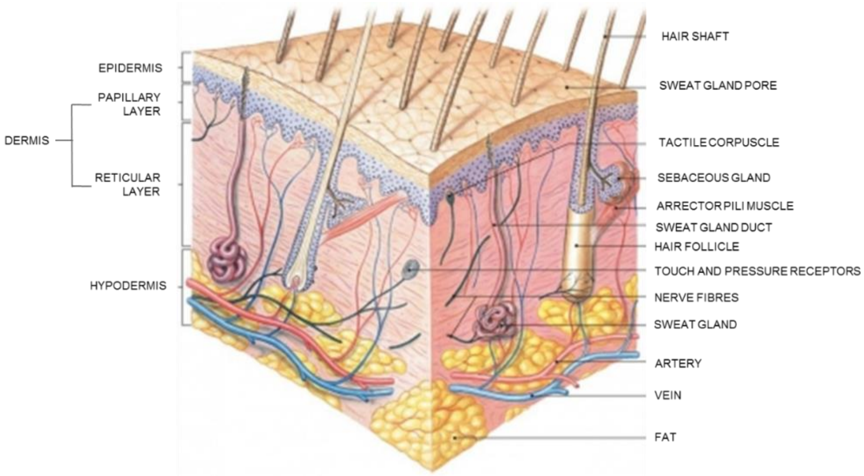

Figure 5 Diagrammatic section of the skin, showing the structure of the dermis and the accessory skin structures. From Martini et al. 2013.

1.4.4 The skin as sensory organ

The skin is involved in the reception of sensory information which is then relied upon the central nervous system. This sensory function is essential for temperature sensation and also regulation. In the skin, in fact, are located receptors for the general senses. These sensors are classified according to the nature of the stimulus that excites them. Important receptor groups include thermoreceptors (sensitive to temperature), mechanoreceptors (sensitive to physical distortion, stretching or twisting resulting from touch, pressure and body position), nociceptors (sensitive to pain) and chemoreceptors (sensitive to chemical stimuli).

1.4.4.1 Thermoreceptors

Temperature receptors are free nerve endings located on myelinated and unmyelinated fibres. Warm and cold receptors differ in number and firing rate. Cold receptors are three or four times as numerous as warm receptors. The firing rate depends upon the type of myelination of the fibre they are connected to. Cold fibres are mainly represented by A delta (Aδ) fibres which have thinly myelinated axons that conduct signals between 5-30 ms^{-1} (Campero et al., 2001). The C unmyelinated fibres represent the warmth fibres (McGlone et al., 2014) that transport warm signals at a much slower speed, between 0.5 and 0.7 ms^{-1} (Hensel 1981). Cold fibres are activated between 15-38 °C and reach the peak between 23-28 °C. Warm fibres are activated at around 33 °C and reach their peak at approximately 42 °C (Bullok et al. 2001). These receptors increase or decrease their firing rate based on the direction and magnitude of the change in temperature and this ultimately influences the individual thermal sensation (Bullock et al., 2001). Therefore, thermal sensation is mediated by Aδ and C afferent fibres which, once have transduced and encoded the thermal stimuli, transmit this thermal information to the central nervous system (Schepers and Ringkamp 2010).

The location, density and distribution of thermoreceptors play an important role in determining thermal sensation. Cold and warmth thermoreceptors distribution varies across the body; this in part explains body regional differences in thermal sensitivity.

The involvement of recently discovered transient receptor potential (TRP) ion channels, known as thermoTRP channels, in peripheral thermo-sensitivity and therefore thermoregulation, has been studied intensively. The mammalian TRP superfamily consists of 30 channels divided into six subfamilies known as the TRPC (canonical), TRPV (vanilloid), TRPM (melastatin), TRPML (mucolipin), TRPP (polycystin), and TRPA (ankyrin) (Romanovsky 2007). Of these, the heat-activated TRPV1-V4, M2, M4, and M5 and the cold-activated TRPM8 and A1 are often referred to as the thermoTRP channels. ThermoTRP channels are activated within a relatively narrow temperature range, however, the range that they cover cumulatively is very wide: from noxious cold to noxious heat (Fig 6) (Romanovsky 2007). Furthermore, they cover this temperature range in an overlapping fashion, and their activities have different sensitivities to temperature. Figure 6 shows the dependence of the activity of cold-activated (blue) and heat-activated (red) thermoTRP channels on temperature. The thresholds of activation and temperatures of maximal activation are based on the activity of the channels in heterologous systems.

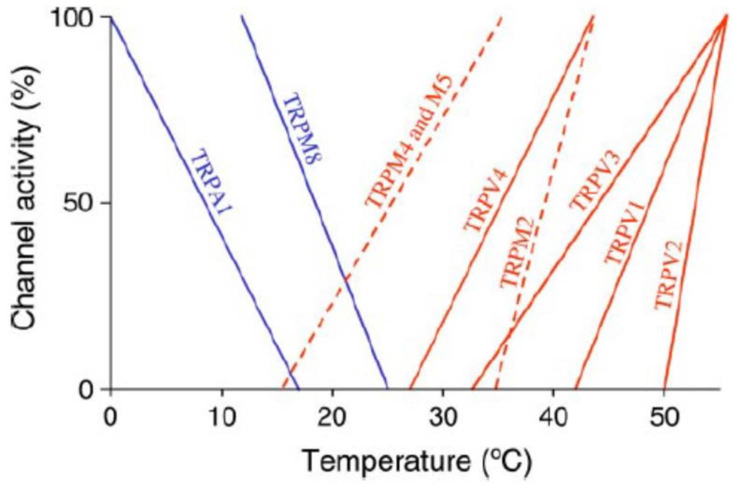

Figure 6 Schematic representation of the relation between activity of thermo-TRP channels and temperature. The figure is adapted from Patapoutian et al.(2003). Information on the TRPM2 is added based on Togashi et al. (2006); information on the TRPM4 and M5 is added based on Talavera et al. (2005); the added lines are dashed.

1.4.4.2 Tactile receptors

Tactile receptors are a specific type of mechanoreceptors which provide sensations of touch, pressure and vibration (McGlone and Reilly 2010). These include corpuscular and non-corpuscular (free nerve endings) nerve endings. The free nerve endings are situated between epidermal cells and their structure is not different from that of the free nerve endings providing temperature sensations (Martini et al. 2013). The root hair plexus is made up of free nerve endings, stimulated by hair displacement and also respond to distortion and movement across the body surface.

The Merkel's disks are fine touch and pressure receptors, mainly located in the deepest epidermal layer of the hairless skin. The Meissner corpuscles are sensitive to fine touch and pressure as well as low-frequency vibrations. They are abundant in eyelids, lips, fingertips, nipples and external genitalia. Pacinian corpuscles are large receptors sensitive to deep pressure, pulsing and high-frequency vibrations. Ruffini corpuscles are sensitive to pressure and distortion of the skin and are located in the deepest layer of the dermis.

1.4.5 Sensation and perception

The sensory receptors monitor the conditions in the body and in the thermal environment. In the sensation process the physical stimulus, together with its physical properties are registered through the sensory organ. The sensation then arrives to the central nervous system (CNS) in the form of action potential through an afferent fibre (sensory, ascending). Most of the processing of this sensory information occurs in the sensory pathways in the spinal cord or in the brain. For instance, the posterior column pathway sends fine touch, pressure and vibration sensations to the cerebral cortex. The sensory cortex presents a miniature map of the body surface. This map results distorted in that, the area of the sensory cortex dedicated to a particular region is proportional no to its size, but to the number of sensory receptors that region contains (Martini et al. 2013). However, in the CNS, the sensation is organised, translated and integrated into the process of perception. These two main processes are arranged into a circular sequence of events (Goldstein 2002), summaries in a diagram in Figure 7.

In this diagram (Fig 7), the first step is represented by the environmental stimulus, which could be anything is in the surrounding environment. The environmental stimulus is then detected by the receptor. Following from this, in the nervous system, the transduction of the stimulus occurs. In this process, the energy of the stimulus is transformed into electrical energy (action potential). The electrical energy will activate a series of neurons in the nervous system, in an event defined as neural processing (Goldstein 2002). The neural processing occurs through the interconnection between various pathways and it is extremely important because it allows the flow of the signals which will then create the perception process. The perception is generated when the electrical signals, provided by the stimulus, are transformed in the CNS into a conscious sensory experience (Goldstein 2002). For instance, one can see a cat but it is not sure whether the cat has been perceived. If the cat has been perceived then other actions are required, such as recognition of the stimulus (e.g. this is a cat and not a butterfly) and an action can be taken based on the perception (e.g. the person can walk closer to the cat to stroke it). Recognition (when the stimulus is placed into a category) and action (motor activity) represent important outcomes of the perceptual process. An important step in the perceptual process placed above the 'neural processing' is knowledge. The knowledge is any information that the person, perceiving something, brings to the situation, such as things previously learned, perceived or happened. This suggests that perception can be influenced by past sensory experiences.

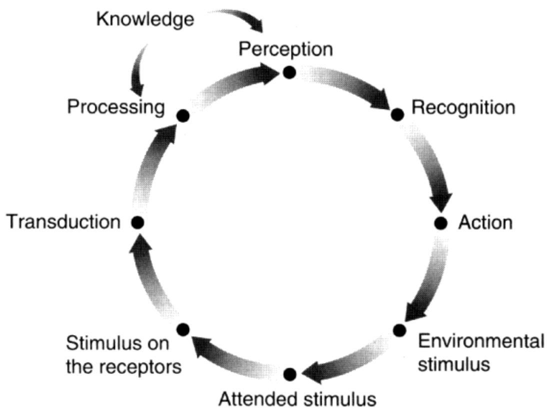

Figure 7 Schematic representation of the perception process, from Goldstein (2002).

1.4.6 Sweating

The evaporation of sweat from the skin surface is considered to be the determining pathway for body heat loss when environmental temperatures rise, during exercise (Kerslake 1972) or when heat loss is restricted, for instance by clothing (Havenith 2003). Evaporation of sweat occurs when sufficient heat from the skin causes sweat to change from liquid to gas phase. This process requires 2430 joules per gram ($J \cdot g^{-1}$) of water at 30 °C (Gibson and Charmchi 1997). In addition to visible sweat, approximately 20-25 mL of water evaporates through the skin surface and the alveolar surfaces of the lungs as 'insensible perspiration' (Kuno 1956). The insensible perspiration accounts for nearly one-fifth of the average daily body heat loss and its rate remains constant throughout the day (Kuno 1956).

1.4.6.1 Sweat glands

It has been estimated that there are approximately 2-5 million sweat glands over the body (Kuno 1956; Szabo 1962). These include three types of sweat glands: apocrine, eccrine and apoeccrine. Apocrine sweat glands are always associated with air follicles. These glands are related to psychological stimuli, produce a smaller amount of sweat than the eccrine glands and the produced sweat is viscous and responsible for the odour (Sato et al. 1989). Apocrine sweat glands are mainly located in restricted body regions of forehead, axilla, palmar, plantar and pubic regions. Eccrine sweat glands are related to the thermoregulatory function and are distributed over the general skin surface (Kuno 1956; Sato et al. 1989). The greatest number of eccrine glands can be found on the forehead, followed by the trunk and the smallest number is present in the body extremities (Kuno 1956). Apoeccrine glands are a hybrid between apocrine and eccrine glands. This kind of gland only develops during puberty and is located only in the adult axilla. Apoeccrine glands produce about ten times more sweat than the eccrine ones.

Values for regional sweat glands density (glands·cm^{-2}) have been gained from cadaver studies (Szabo 1962). Specifically, the greatest densities were observed on the soles, forehead and cheeks (320 ± 60) and the lowest values were on the back, buttocks, lower legs, upper arms and thighs.

1.4.6.2 Gross sweat loss and regional sweat rate

Extensive work has been conducted by Smith and colleagues to quantify the total amount of sweat produced (gross sweat loss) during continuous running at a low and high intensity in male and female athletes and untrained males (Smith and Havenith 2011; Smith and Havenith 2012). Additionally, this research has provided quantitative data on body regional sweat rate, measured for the first time simultaneously in large body areas (Havenith et al. 2008; Smith and Havenith 2011; Smith and Havenith 2012).

Higher gross sweat loss (GSL) was identified in male compared to female athletes and also untrained males. These differences were mainly due to the selection of the same relative workload (percentage of VO_{2max}) across the three groups. In this condition, due to their higher aerobic fitness level, male athletes worked at higher absolute workload compared to the other two groups. Neverthelss no significant differences in GSL where observed between male and female athletes at lower work intensity (55% of VO_{2max}). In line with this, when normalising work rate for body surface area ($W \cdot m^{-2}$) no differences in work rate were observed between male and females athletes, indicating that at low exercise intensity the males were working harder because of their larger size. At higher exercise intensity (75% of VO_{2max}) female athletes showed greater sweat rise per unit increase in work rate (sweat sensitivity), indicating a decrease in sweating efficiency in females compared to males, as work intensity increases. Male athletes also presented higher body regional sweat rate data compared to female athletes and untrained males, for the same relative workload.

In these studies, despite large variations, consistent patters of body regional sweat rate were observed between participants and across the three groups (Smith and Havenith 2011; Smith and Havenith 2012). Specifically, the highest sweat rates ($g \cdot m^{-2} \cdot h^{-1}$) were observed in the body regions of the lower posterior torso and forehead (Fig 8). On the other hand, the lowest sweat rates were observed on the fingers, thumbs and palms (Fig 8). A medial to later decrease in sweat rate was evident on the torso and a proximal to distal increase in sweat rate was observed on the arms. On the head regions, a medial to latera increase in sweat rate was present, however, these differences were not significant, possibly due to the small sample size and to the large inter-individual variation in sweat rates. Finally, in most body regions sweat rate increased with the increase in exercise intensity, with exception of the feet.

These data made available fundamental knowledge on sweat rate patterns across the human body that, in part, might support the process of clothing development. However, crucial information regarding the amount of secreted body sweat that is absorbed and retained by the worn garments and on how this distributes across different garment regions is still unknown. Additionally, a close cooperation is needed between different experties, i.e. human physiology, textile engineers and clothing designers in order to determine how the human sweat maps can be translated into garments with efficient moisture absorption and transport features.

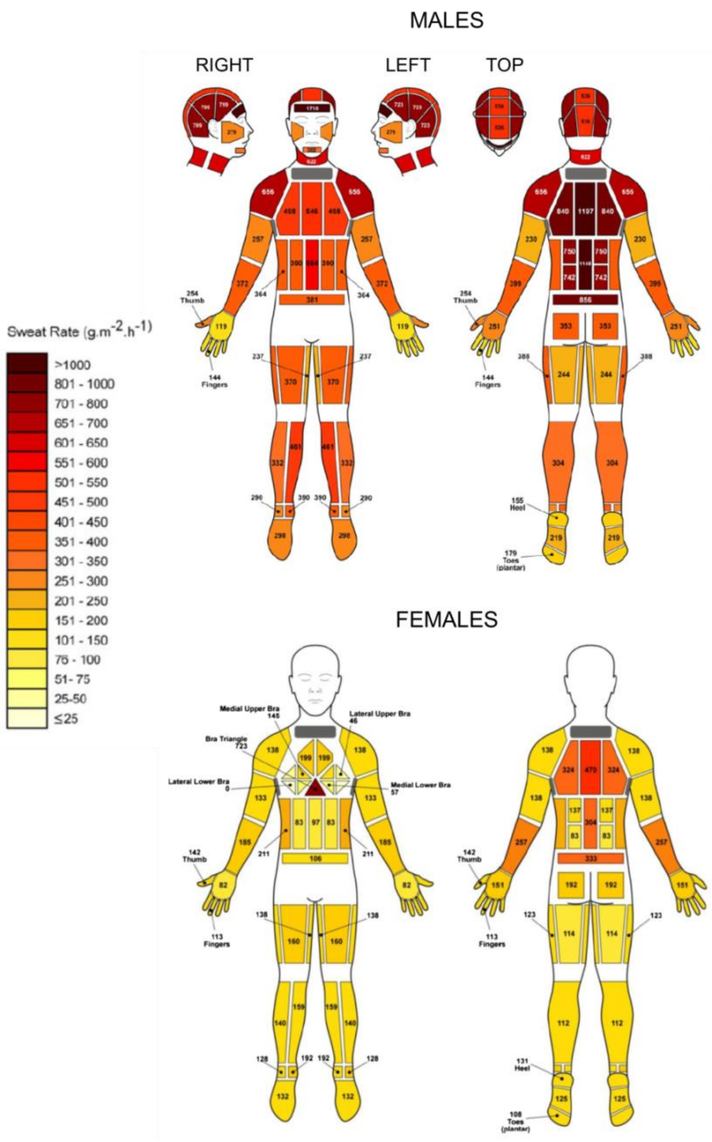

Figure 8 Regional median sweat rates of male and female athletes from Smith and Havenith (2011, 2012).

1.4.7 Skin wettedness and sweating efficiency

Evaporation of sweat from the skin surface represents a crucial thermoregulatory function as it provides the cooling necessary to match body metabolic heat production with heat loss (Gagge and Gonzalez 2011). Sweat evaporation involves two phases: total evaporation and partial evaporation phase (Tam et al. 1976). In conditions of low metabolic heat production, e.g. during the initial stages of the physical exercise activity, sweat production is low and complete evaporation occurs, this maintaining the skin relatively dry. With the increase of metabolic heat production, sweat evaporation rate cannot keep up with sweat production rate and only partial evaporation will occur. In this phase, the evaporation rate is mainly determined by the maximum evaporative capacity (E_{max}). According to the heat balance equation, to maintain thermal balance the required evaporation rate (E_{req}) should be sufficient to keep body heat storage (S) near to zero, according to (Shapiro et al. 1982):

$$E_{req} = M \pm W \pm RES \pm DRY - S$$

Where

M metabolic heat production

W mechanical work

RES respiratory heat exchange

DRY sensible heat loss by radiation and convection

S heat storage caused by the rising core temperature

It is important to note that this thermal equilibrium depends on the efficiency of the secreted sweat to cool down the skin (Gonzalez et al. 2009). As such, when looking at sweat evaporation it is important to consider sweating efficiency (the ratio of evaporated sweat to total sweat production) as well as skin wettedness (ω). Skin wettedness, as a physiological variable associated with sensible and insensible perspiration, was firstly introduced by Gagge (1937). It represents a dimensionless ration between the surface area of the skin covered by sweat that evaporates (A_e) and the total skin surface area of a person (A_d). It is expressed as a decimal fraction, ranging from 0.06, which is the minimal skin wetness value consequent to insensible perspiration, to 1, which represents a fully wet skin (Nishi and Gagge 1977). This ratio is derived from the calculation of the rate of evaporation from the skin, according to (Candas 1987):

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

Where;

E_{sk} evaporative heat loss from the skin

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)

If T_{sk} remains constant, two factors will affect E_{sk} such as air velocity, which will cause modification of the heat transfer coefficient (h_e) and ambient water vapour pressure (P_a), which will affect the water vapour gradient between the skin surface and the surrounding air (Candas et al. 1979). In a hot and dry environment, the evaporative heat capacity (E_{max}) will far exceed the required evaporative cooling (E_{req}), thus, the percentage of wetted skin will be low (Gagge 1937). Nevertheless, the required evaporative rate (E_{req}) may not be attainable in a hot and humid environment, where, due to an increase in partial water vapour pressure in the environment, the maximum rate of evaporation (E_{max}) is low. In these conditions, the control of body temperature becomes difficult, leading to an increase in the skin wettednes. When sweat production surpasses E_{max}, the entire skin surface will be covered by sweat, equating to a skin wittedness of 100% (ω = 1) When the skin surface becomes fully wetted, the further increase in partial water vapour pressure on the skin can cause the evaporative cooling to further drop below the required evaporative cooling, resulting in body heat storage. Skin wettedness can be calculated as the ratio between the actual (E_{sk}) and maximal (E_{max}) rates of evaporation according to (Candas 1987):

$$\omega = \frac{E_{sk}}{E_{max}}$$

The concept of sweating efficiency can be discussed when considering skin wettedness in a hot humid environment. When evaporative heat loss from the skin is restricted, due to a diminished gradient in water vapour pressure between the skin and the environment ($P_{sk} - P_a$) or when wearing protective clothing, higher sweat rate is required to achieve a high level of skin wettedness. When the skin surface becomes saturated with sweat, part of this sweat will be absorbed by the garment (if the clothed human body is considered), part will be 'wasted' through drippage (Gagge 1937; Winslow 1939; Candas et al. 1979; Candas 1987). The sweat that drips across the skin does not contribute to body cooling (Kerslake 1972; Candas et al. 1979). Specifically, it was found that when full skin wettedness is achieved, at least 40% of the secreted sweat drips off the skin without evaporating (Kerslake 1972). Therefore, in this scenario, an elevation in sweat rate will not produce an equivalent increase in evaporative cooling. As such, E_{max} is predominantly determined by the environment rather than the quantity of sweat produced and sweat rates equating to an E_{req} in excess of E_{max} will lead to an inefficient wasteful loss of fluid. This inefficiency in sweat production is commonly recognised as a failure of the thermoregulatory system.

1.4.8 Evaporative cooling in relation to clothing

The traditional method to determine the rate of evaporative heat loss in human is to define the mass change of the clothed body per unit of time, corrected for the rates of respiratory moisture loss and metabolic mass loss (Havenith et al. 2007b). This mass change rate is then multiplied by the latent heat of evaporation (~ 2430 $J \cdot g^{-1}$) to calculate the rate of energy lost by evaporation. In clothed conditions, the produced body sweat has to travel across the clothing barrier through various transport processes. Vapour sweat may be absorbed by the textile fibres and then desorbed; it may condensate on the outer clothing side, if it is colder than the skin, and then may evaporate again. In the clothing microclimate, vapour sweat may also be ventilated directly through clothing openings or, depending on the air permeability of the fabric, it may diffuse through the clothing layer to the environment (Farnworth 1986; Lotens and Havenith 1995; Fukazawa et al. 2003; Fan 2005; Fan and Cheng 2005). As such, evaporative heat loss is traditionally calculated from the mass change of the human-clothing system, due to the assumption that only the moisture vapour that leaves the clothing ensemble contributes to body cooling. However, it was demonstrated that when body evaporative heat loss is calculated from the weight change of the clothed person (clothing with low air permeability) substantial errors cay be made (Havenith et al. 2007b). In particular, it has been observed that the errors can lead to overestimations (+ 22 W) or underestimation (- 58 W) of evaporative heat loss in the heat and in the cold, respectively. With regards to the mechanisms behind these errors, it was shown that when wearing clothing, the latent heat of evaporation of moisture from the skin is not completely taken from the body, the latter leading to an evaporative efficiency that is < 1. Additionally, when ambient temperature is lower than skin temperature, this effect will be compensated by the so-called 'heat pipe effect' (Havenith et al. 2007b). Through this effect, latent heat is transferred from the skin to clothing without losing moisture (weight) from the clothing. As results of this effect, the apparent evaporative cooling efficiency is pushed towards unity first, and at cooler temperatures and for clothes with low permeability, it is pushed even above unity. Knowing these effects it is crucial when estimating heat loss from a clothed person, in order to prevent errors that may put at risks people performing physical exercise.

In the previous paragraph we indicated that when the skin surface becomes saturated with sweat, part of this sweat will be 'wasted' through drippage but, if the person is clothed, another part will migrate from the skin into the garment. The sweat absorbed by the clothing can still contribute to the evaporative cooling of the body. However, when the sweat is in the garment the heat necessary for evaporation is taken from the body but another part may be taken from the environment. This may cause a drop in the evaporative cooling efficiency, i.e. less cooling is provided to the body per gram of evaporated sweat (i.e. the effective latent heat of evaporation is reduced, Fig 9). This phenomenon was firstly described by Burton and Edholm (1955) who pointed out that when moisture evaporates from the skin, it condenses in the clothing and then re-evaporates from the clothing. In this scenario, the evaporative heat drawn from the body will vary according to the distance from the skin to the point of condensation. In line with this, Havenith et al. (2013) demonstrated that the cooling efficiency of evaporation is affected by the location of moisture evaporation in terms of its distance from the skin. Specifically, in this study using a thermal manikin, which allowed direct measurement of evaporative heat loss as well as direct measurement of the mass loss rate due to evaporation, the heat loss from the body, per gram of moisture evaporated (the effective latent heat of evaporation), was calculated. For evaporation from the skin, this value is close to the theoretical value (2430 $J{\cdot}g^{-1}$), however, it starts to drop when more clothes are worn, e.g. by 11% when underwear and an impermeable coverall is worn (Fig 9). When evaporation occurs from the base-layer, the reduction is of 28%, wearing an impermeable outwear. When evaporation takes place in the outermost layer only, the reduction is > 62% (no under clothing) and increases towards 80% when wearing more layers underneath (Fig 9).

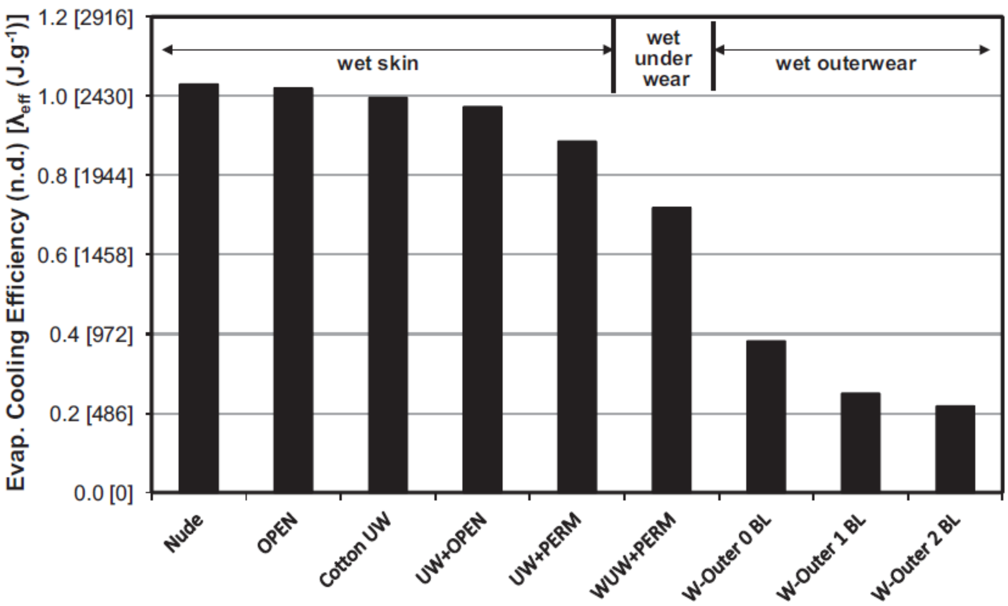

Figure 9 Evaporative cooling efficiency (η_{app}) and effective latent heat of cooling (λ_{eff}) measured in undressed state of for permeable clothing, for different evaporation loci (Havenith et al. 2013).

Similarly, recently it has been indicated that when tight fitting clothes with high wicking properties, (fast sweat transfer from the skin to the garment) are used, the evaporative cooling may also be reduced (Wang et al. 2014). Using a torso manikin, the study of Wang et al (2014) quantified the real evaporative cooling efficiency in different absorption scenarios of a one-layer tight-fitting garment. The experiment comprised three conditions to mimic different absorption phases. In one condition all the moisture was added to the skin of the torso manikin, in another condition, 50%

of the moisture was on the skin and 50% in the garment and finally in the third condition all the moisture was added to the clothing. In line with previous findings (Havenith et al. 2013), it was indicated that the real evaporative cooling efficiency linearly decreases with the increasing amount of total produced sweat evaporated away from the skin. Additionally, it was shown that for the same absorption phase, fabric thickness plays an important role in maintaining cooling efficiency. Particularly, fabric thickness between 0.5 and 0.8 mm is recommended to maintain adequate evaporative cooling efficiency (Wang et al. 2014).

Therefore, in conditions where only a small fraction of produced sweat can evaporate (i.e. high humidity in the environment or the use of personal protective clothing) it would be best if evaporation could occur directly from the skin. Nevertheless, when both the skin and clothing are wet and a large amount of ventilation takes place, having the extra evaporation from the fabric, besides that from the skin, may be beneficial. Finally, fabrics with an optimum thickness, able to accommodate a sufficient amount sweat to prevent sweat drippage (considered as waste) but still able to maintain high sweating efficiency (no too thick), should be selected.

1.4.9 Skin wetness perception

Skin wettdness as thermophysiological parameters has great importance in terms of sweating efficiency and human thermal balance. Beside this, Gagge also acknowledged the role of skin wettdness in the context of thermal comfort (1937). The level of skin wettdness, in fact, was demonstrated to be positively correlated with thermal discomfort. It has been identified that a state of thermal comfort can be achieved when skin wettdness remains below 0.3, this recognised as the thermal comfort limit (Gagge 1937). This important link between physical skin wettdness and thermal comfort exists thanks to the human ability to perceive skin wetness, this despite the lack of cutaneous moisture receptors (Clark and Edholm 1985). The lack of hygro-receptor in the human skin has led a number of researchers to investigate the cutaneous sensory mechanisms underpinning skin wetness perception. This extensive research has also been accentuated by the high impact that skin wetness perception plays on the onset of discomfort when wearing clothing (Hollies et al., 1979; Plante et al., 1995a).

Bentley (1900) was one of the first researchers that hypothesised the involvement of thermal sensation in the perception of wetness. In his 'synthetic' experiment, he asked a group of participants to dip their index finger, covered by a sheath, into water at warm and cold temperatures. Results indicated that, although no direct contact with the water occurred, participants reported a perception of wetness, which was greater in the cold water condition. This suggested for the first time the 'synthetic' nature of wetness perception, evoked by thermal stimulations. Sensations of wetness on the skin can occur through two types of thermal stimulations, one associated to the thermal conductivity of the water and the second one elicited by the cooling provided by the evaporation of the water. The thermal conductivity of the water is higher than that of the air. Thus, when the skin is wet heat is conducted away from the skin faster, compared to when it is dry. Thus, water causes a cooling sensation despite having the same temperature as the skin or the air (Bergmann Tiest et al. 2012b). In 1944 Hock et al. observed that wet fabrics produced a chilling effect and that this effect was higher in fabric with good contact with the skin. Subsequently, in 2005 Li indicated that the perception of a wet fabric is related to the transient heat and moisture transfer between the fabric and the skin. This was also supported by Kaplan and Okur (2009) who observed that wet clothes in contact with the skin causes cooling sensations and changes in skin temperature. The effect of heat extraction from the skin, as modulator of wetness perceptions, was also observed by Bergmann Tiest et al. (2012). In this study, they used fabric materials with high thermal conductivity, able to extract higher amount of heat from the skin. These materials, apart from being perceived cooler, were also perceived as wetter, compared to standard fabrics (lower thermal conductivity), despite presenting same water content. Later on, to show the contribution of cooling sensation to the perception of skin wetness, Filingeri et al. (2013) demonstrated that the application of cold-dry stimuli (using a thermal probe), which provided a cooling rate of 1.4 to 4.1°C, could evoke a clear perception of wetness, even in absence of water.

Evaporation of sweat also extracts heat from the skin, cooling it down and resulting in wetness sensations (Bergmann Tiest et al. 2012). The difference between the effect of thermal conductivity and evaporation consists in the fact that evaporative cooling is sensed from a thin layer of moisture on the skin, whereas an increase in conductive cooling (thermal conductivity) is associated with a larger volume of liquid. Ackerley et al. (2012) observed that when applying different amounts of water to fabrics, the amount of residual moisture left on the skin was different. The water evaporated at slightly different rates and wetness perception changed accordingly to the amount of water left on the skin, this confirming the link between moisture evaporation, cooling sensation and wetness perception. Nevertheless, in the context of cutaneous wetness perception, the role of evaporative cooling, induced by sweating in exercise has not received as much attention as conductive cooling (application of a cold/wet stimulus on the skin).

Tactile cues are also involved in the perception of wetness. Specifically, the mechanical pressure of the liquid on the skin can contribute to the perception of wetness. This can take place when the body is immersed in a liquid or when water drops on the skin. Additionally, when manipulating a wet fabric or when wearing wet clothing, other tactile-related sensations, i.e. stickiness sensations, can arise from the mechanical interactions between the wet material and the skin (Bergmann Tiest et al. 2012). In fact, in wet state fabrics tend to cling to the skin, increasing the attractive force at the fabric-skin interface, this resulting in sensations of stickiness which contribute to the perception of wetness (Connor et al., 1990). Furthermore, the presence of water in a textile material in contact with the skin increases skin friction (Zimmerer et al., 1986). Gwosdow et al. (1986) observed that the presence of moisture increases the friction force required to pull a fabric across the skin, this being positively correlated with the level of subjective moisture discomfort experienced. In support, Kenins (1994) found that water on the skin has an effect on friction which is larger than the effect of fabric's surface properties (e.g. hairiness and smoothness), fabric weight and yarn diameter.

1.4.9.1 Model of skin wetness perception

Based on the scientific evidence provided in the last decade and in line with more recent studies (Filingeri et al. 2013; Filingeri et al. 2014b; Filingeri et al. 2014a; Filingeri et al. 2015; Filingeri and Havenith 2015) the mechanisms underpinning skin wetness perception in humans have been summarised in a model (Filingeri and Havenith 2015). This model (Fig 10) comprises biophysical (thermal and tactile inputs induced by the presence of moisture on the skin), neurophysiological (central integration of afferents inputs thermoreceptors and mechanoreceptors) and psychophysiological mechanisms (i.e. perceptual inference operated by cortical and sub-cortical somatosensory and association areas) which allow humidity and wetness detection in humans. In this model, the skin contact with moisture (1) generates thermal and tactile inputs which are peripherally detected by specific nervous structures sensitive to thermal and mechanical stimuli, such as thermoreceptors (2) and mechanoreceptors (3), respectively. The wet inputs evoke cutaneous thermal (4) and tactile sensations (5) which are then integrated in the central nervous system (6). Repeated exposures to these stimuli (past sensory experience) (7) contribute to generating a neural representation of a typical wet stimulus via learning mechanisms. At this point, only if the learnt combination of stimuli (i.e. coldness and stickiness and/or pressure sensation) occurs, wetness will be perceived (8).

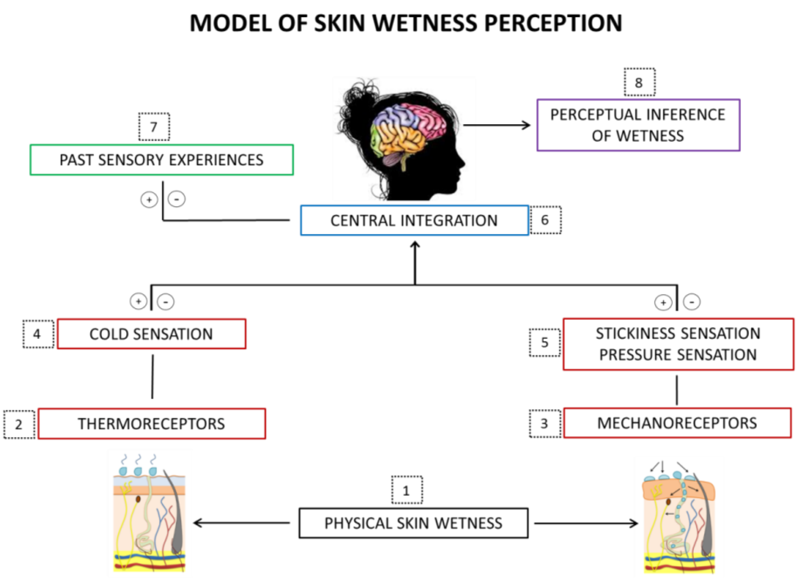

Figure 10 Schematic representation of the model of skin wetness perception in humans.

1.4.9.2 Threshold studies

In 1990 Sweeney & Branson attempted to answer two basic questions related to the perception of skin wetness. The first question was '*at what level of intensity is a wet stimulus perceived by a human?'* Following from this, the second one was '*how much this intensity needs to change before an individual can detect a difference in the perception of the wet stimulus?'* (Sweeney and Branson 1990a). Using a cotton/polyester blend textile of 25 cm^2, applied on the upper back, it was found that 0.024 $mL\cdot 25cm^{-2}$ (0.00096 $mL\cdot cm^{-2}$) was the minimum amount of water necessary to evoke a sensation of wetness. With regards to the second question, 0.034 $mL\cdot 25cm^{-2}$ (0.0013 $mL\cdot cm^{-2}$) was the minimum amount of stimulus change required to produce a difference in the perception of wetness.

In a following experiment, Sweeney & Branson (1990b) studied the relationship between wet stimuli and wetness sensations. By using a psychophysics scale, thirteen participants scored a range of different water amounts added to a 25 cm^2 of cotton/polyester blend fabric, applied on their upper back. It was found that wetness sensation increased as the amount of moisture in the fabric was also increased, showing for the first time the link between the amount of physical wetness and the perception of wetness. Nevertheless, textile factors, such as fibre content, surface texture, surface area, thickness, structure, as well as clothing factors, for instance, design and fit, could modulate and have an impact on wetness perception. Therefore, future studies should include the contribution that clothing and textile factors have on the perception of skin wetness.

1.5 Clothing

Clothing ensures modesty, reflects the status of the wearer, represents people's culture, and is used as trends in fashion. More importantly for people's health and survival, clothing provides the human body with protection from environmental factors. Clothing manufactures are constantly engaged in a development process which is able to meet the sports/ work activity demand as well as the requirements for thermoregulation during physical exercise. This requires a clothing development and evaluation process typically articulated in a series of steps involving textile and clothing testing, including instrumental and often human assessments.

The next paragraphs provide a critical and comprehensive examination of thermal and moisture properties of clothing. The origination and application of the research methodology as well as the test methods developed to assess textiles and clothing properties is reported and discussed.

1.5.1 Clothing comfort

An important approach used to evaluate clothing performance and individual's satisfaction is to consider the comfort aspect (Hatch, 1993). A widely accepted definition of comfort refers to 'a neutral state in which an individual experience no pain or discomfort' (Hatch 1993). Within the comfort concept, Slater (1985) identified three sub-categories and reported that comfort involves the balance of physiological, psychological and physical aspects of the person and the environment. The three main sub-categories of comfort are: psychological, sensorial/tactile and physiological (Slater, 1985).

Psychological comfort relates to the comfort state of the individual in relation to its role, value and social being (Kamalha et al., 2013). Environmental factors, such as occasion, geographic location, climatic condition, socio-cultural setting, norms and historical importance, are part of the psychological comfort aspect.

Sensorial/tactile comfort refers to the various sensations experienced by the wearer when clothing is in contact with the skin (Kaplan & Okur 2009). The term 'fabric hand' or 'haptic' is commonly used when assessing sensorial properties of textiles, such as smoothness, roughness, prickliness, stickiness, scratchiness, softness and stiffness (Kamalha et al. 2013). When touching a textile, changes in temperature are also sensed and perceived such as warmth, coolness, breathability, hotness and chilliness (Bishop 1996). Sensations related to the presence of moisture in fabrics represent other 'hand' perceptions and these include clamminess, dampness, wetness, stickiness and clingy sensation. Finally, fabric hand includes pressure sensations, such as snugness, looseness, lightweight, heaviness, softness and stiffness.

Thermophysiological comfort and thermal comfort are both commonly used to describe clothing comfort with reference to human thermal and moisture sensations. Thermal comfort is expressed by the British Standard BS EN ISO 7730:2005, as 'the condition of the mind which expresses satisfaction with the thermal environment'.

In summary, comfort is a complex and multifactorial concept, involving both thermal and non-thermal factors and can be related to a wide range of conditions, i.e. exercise, resting and extreme ones (Fourt and Hollies 1970). Sensations of discomfort can affect human productivity, physical performance as well as cognitive task performance (DenHartog and Koerhuis 2017) and satisfaction. As such, particular attention should be given to the sensorial and thermal aspects of comfort when developing clothing for work, sport and protection applications.

1.5.2 Thermal comfort

When wearing clothing a microclimate is created between the skin and the garment. The perception of humidity as well as temperature, which characterise this microclimate, affects human thermal comfort. Gagge et al. (1937) investigated the sensory comfort and thermal sensation of unclothed individuals when resting, under steady-state and transient conditions, ranging between 12 °C and 48 °C. These perceptual responses were then related with the corresponding physiological responses. It was indicated that, when exposed to warm environments, thermal comfort and neutral temperature sensations ranged between 28-30 °C (environmental temperature). Discomfort was perceived when exposure to cold environments caused reductions in skin temperature and exposure to the heat caused sweating. Interestingly, it was found that thermal discomfort was an important stimulus for behavioural thermoregulatory adjustments. Later on, Gagge et al. (1969) conducted a study investigating the relations between thermal comfort and physiological responses during exercise at various ambient temperatures. It was indicated that after 30-40 min of steady exercise, temperature sensation ranged from cool to hot and it was mainly affected by sensory mechanisms occurring at skin level, such as skin and ambient temperature. On the other hand, thermal discomfort was affected by thermoregulatory mechanisms, such as skin sweating and skin conductance. In line with this, it was indicated that temperature sensations are mainly derived from the cutaneous thermoreceptors, whereas thermal discomfort is a general thermal state resulting from the integration of afferent signals from cutaneous and internal thermoreceptors (Hensel 1981). For this reason, the measurement of thermal sensation and thermal discomfort is normally distinguished.

In 1970, Fanger developed a mathematical model to identify the neutral thermal comfort zone of men, using a combination of different clothing and activity levels (Fanger 1970). In the model, mean skin temperature and sweating were used as physical parameters to predict comfort. Subsequently, based on Fanger's work, the American Society for Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) developed indices of thermal sensation to predict comfort under different combinations of clothing insulation, metabolic rate, air temperature and wet-bulb temperature (Gagge et al. 1986). In 1985 Fanger in the standard ISO 7730:2005 introduced a definition of thermal comfort, indicated as 'the condition of the mind that expresses satisfaction with the thermal environment'. On the other hand, dissatisfactions, caused by warm or cold sensations, can be expressed by the PMV and PPD indices. The PMV index is the Predicted Mean Vote, used to estimate thermal sensation of the whole body, using a seven-point scale, ranging from cold to hot. The PPD index refers to the Predicted Percentage of Dissatisfaction. The ISO standard recommends a PMV within the range of -0.5 to +0.5, implying a PPD lower than 10%. When the PMV is zero, the optimal operative temperature is achieved, this being function of activity level and clothing. The operative temperature defines the uniform temperature of an enclosure in which an occupant would exchange the same amount of heat by radiation and convection as in the actual non-uniform environment. In Figure 11 illustrated is the optimal operative temperature that can satisfy most people wearing given clothing and at a specific activity level.

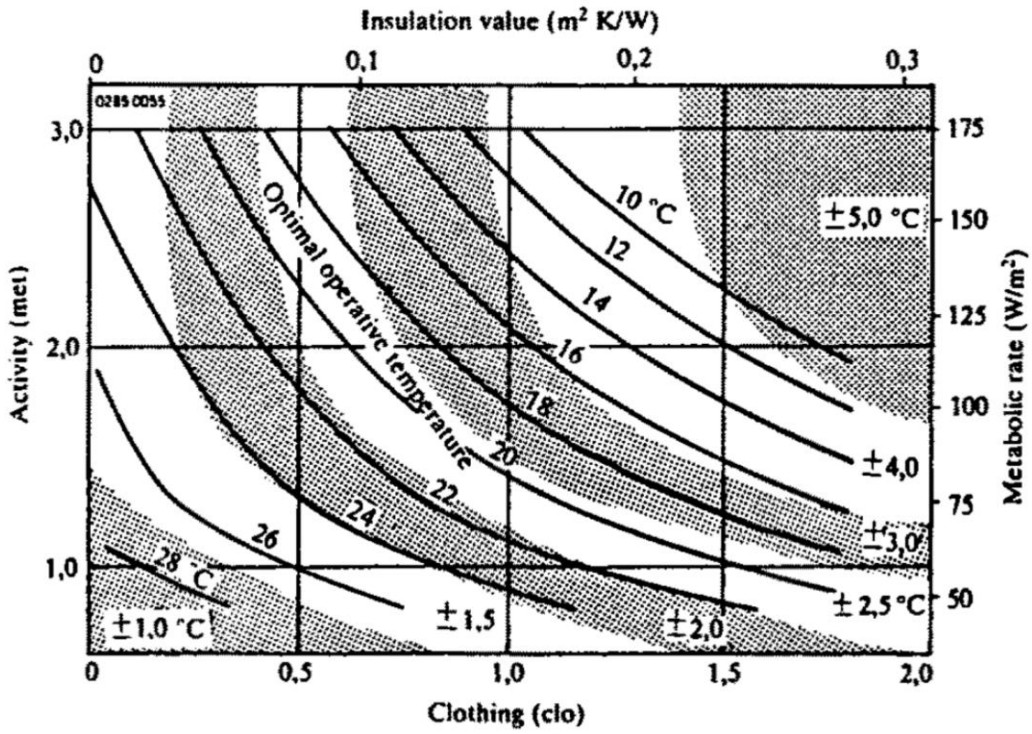

Figure 11 The optimal operative temperature (corresponding to Predicted Mean Vote (PMV) = 0) as a function of activity and clothing. The shaded areas inform about the comfort range + At around the optimal inside temperature, which corresponds to -0.5<PMV<+0.5 from Fanger (1986).

Later on in 1986, Gagge proposed another PMV vote, defined as PMV*, by replacing the operative temperature from Fanger's comfort equation with a Standard Effective Temperature (SET). SET is an index temperature describing the dry bulb temperature of the standard environment at 50% relative humidity that causes same heat exchange for the same thermal stress, skin wettdness and mean skin temperature. In this way, the new PMV* is able to respond to thermal stress in relation to heat load and heat strain by changing humidity of the thermal environment and water vapour permeability of clothing.

1.5.3 Heat and moisture transfer

In the previous sections, the mechanisms involved in the perception of thermal comfort have been presented. These perceptions are formulated based on physical stimuli triggering cutaneous and internal thermoreceptors. These stimuli are generated by external factors, especially by clothing, mostly in contact with the body. Clothing stimulations include heat transfer (convection and radiation), moisture transfer (diffusion, absorption, wicking and evaporation) and mechanical interactions (pressure and friction).

The coupled process of heat and moisture transfer in fabrics is important to understand thermal comfort and balance while wearing clothing. In the process illustrated in Figure 12, the fabric is an element packed with fibres, characterised by area, thickness and porosity. The fabric is exposed to a temperature and moisture gradient, therefore water vapour diffuses through the interspace of the fabric and is absorbed and desorbed by the fibres.

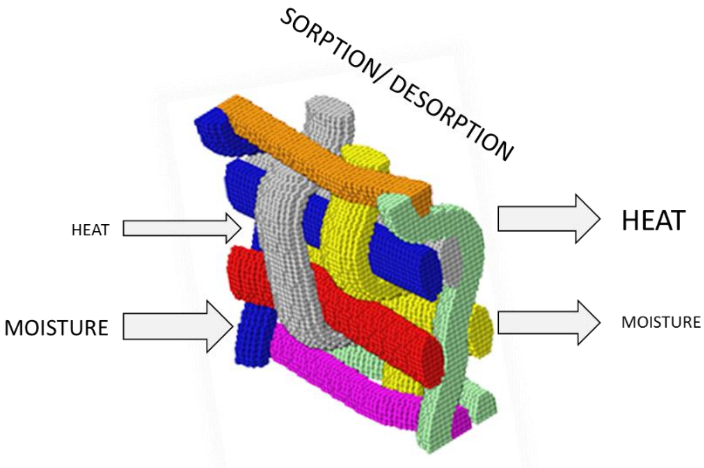

Figure 12 Coupled heat and moisture transfer in fabric.

Based on 'how easily' moisture is absorbed, fibres are classified into two groups: hydrophilic fibres, which can absorb water or moisture in an 'easy' way, and hydrophobic fibres, which absorb moisture 'less easily'. Additionally, under the same humidity condition, the amount of moisture absorbed by different fibres from the atmosphere depends on their regain. Moisture regain is the ability of a dry fibre to absorb moisture from the atmosphere under a set condition of humidity and can be determined as follow:

$$Regain\ (\%) = \frac{Mass\ of\ conditioness\ specimen - Mass\ of\ dry\ specimen}{Mass\ of\ dry\ specimen} \cdot 100$$

In the next paragraphs heat and moisture properties of clothing are discussed.

1.5.4 Thermal resistance

The clothing barrier is formed by the textile material, the air enclosed in the material and the still air layer that is bound to its outer surface.

When considering a fabric, without including the still layer of air next to it (outside environment), the thermal resistance to the heat transmission from the skin to a textile material (and vice versa) is defined as intrinsic (or basic) thermal resistance or insulation. The standard BS EN ISO 11092:2014 defines thermal resistance (R_{ct}) as the temperature difference between two faces of material divided by the resultant heat flux per unit area in the direction of the gradient; it is expressed in square metres kelvin per watt ($m^2 \cdot K \cdot W^{-1}$) or square metres per degree Celsius per watt ($m^2 \cdot °C \cdot W^{-1}$). Heat transfer through textile materials consists mainly of conduction and radiation (Havenith 1999). For most clothing materials the volume of air enclosed is far greater than the volume of the fibres. Therefore, the insulation mainly depends on the thickness of the material (that is the enclosed air layer) and less on the fibre type (Havenith, 1999) (Fig 13). The fibres mainly affect the amount of radiative heat transfer, as they reflect, absorb and re-emit radiation. Thermal insulation also decreases with the increase in fabric density (Ozkan and Meric 2014). Fabric density is obtained by dividing the weight of the fabric by its thickness. In fact, the thermal resistance of the air is higher than that of the fibre. As the fabric density becomes lower, the air gap between the textile fibres increases and the resistance to the heat transfer (thermal resistance) increases.

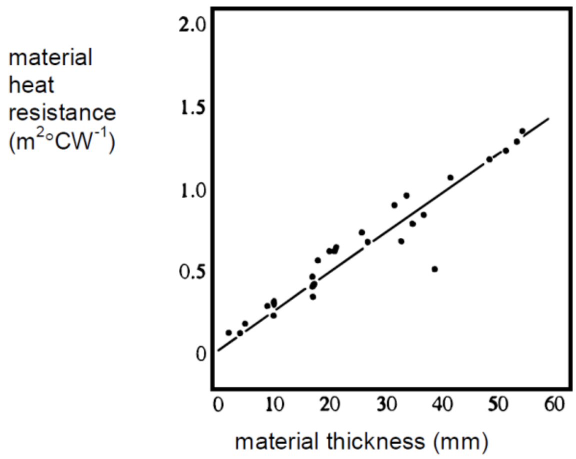

Figure 13 Relation between clothing material insulation and the material thickness (Havenith and Wammes in Lotens 1993).

When not only the textile materials are considered, but also the actual insulation of the material in a garment or when clothing consists of more layers, the dry thermal resistance provided by a textile fabric plus the surrounding air layer becomes important and is defined as total thermal resistance or insulation. In 1941, the *Clo* unit was for the first time proposed by Gagge et al. (1941). One Clo is defined as the intrinsic thermal insulation of a typical business suit required to keep a sedentary person comfortable at 21°C and it has an average value of 0.155 $m^2 \cdot °C \cdot W^{-1}$. In this case, the m^2 term in this unit refers to the surface area of the body.

Garment fit is another factor to take into account when considering clothing insulation. When clothing fits tightly, the air gap between the inner clothing surface and the body skin is smaller and less air is included than when it fits loosely. In support, it has been shown that tight-fitting garments can reduce thermal insulation, whereas loose-fitting garments are more prone to wind and walking movement-induced reduction in insulation (Havenith et al. 2007; Ho et al. 2011). Air movement (e.g. in presence of wind) also greatly affects clothing insulation. This, in fact, can disturb the still air layer on the outer clothing side but also the air layers in the clothing ensemble, by entering through clothing openings or, based on the air permeability of the outer clothing layer, by penetration of the clothing fabric. Another important parameter which can affect clothing insulation is the garment movement. The garment can be moved by both wind and wearer movements. The wind can compress the garment against the skin, reducing the thickness and causing air movement into the garment. Similarly, movements of the wearer can pump air between different clothing layers or force its exchange with the environment. In general, motion has an effect on enclosed and surrounding air layers, whereas wind mainly affects the surrounding air layer and the air layer under the outer garment (Havenith, 1999). An empirical relationship has been derived that quantitatively describe the effect of wind, human movement and outer layer air permeability on clothing thermal resistance (Havenith & Nilsson, 2004).

1.5.5 Evaporative resistance

When exercising or exposed to hot conditions, sweat is produced and evaporation occurs in order to lose heat. The fabric resistance to this vapour sweat transfer is the evaporative resistance or water-vapour resistance. The latter together with the thermal insulation provides the total effect of clothing on heat (dry and evaporative) transfer. The standard BS EN ISO 11092:2014 defines basic (without the surrounding air layer) water-vapour resistance (R_{et}) as the water-vapour pressure between the two faces of a material divided by the resultant evaporative heat flux (this may consist of both diffusive and convective components) per unit area in the direction of the gradient; it is expressed in square metres Pascal per watt ($m^2 \cdot Pa \cdot W^{-1}$). The partial vapour pressure at the skin (hot plate) is assumed to be the saturated vapour pressure at the skin temperature, whereas the partial vapour pressure in the air is related to the relative humidity.

As for thermal insulation, the thickness of the clothing material (normal permeable), mostly determines clothing vapour resistance (Havenith 2002; Havenith 1999, Fig 14). Since the volume of the fibres is usually lower compared to the enclosed air volume, the resistance to the diffusion of water vapour through the garment is mainly determined by the thickness of the enclosed still air layer. However, with thin materials, the fibre component has a major role because their different weave characteristics can affect the diffusion properties more than in a thick material (Havenith 1999). On the other hand, the use of coatings, membranes or the application of others treatments to the fabrics will have a major effect on water-vapour resistance and its relationship with fabric thickness is then lost.

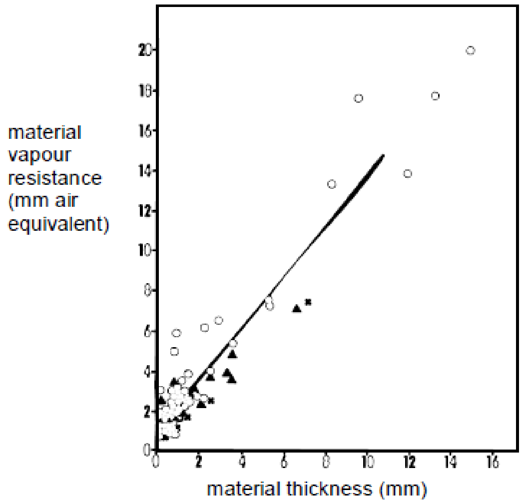

Figure 14 Relation between clothing material vapour resistance and the material thickness (Lotens 1993).

1.5.6 Liquid moisture transfer

On its way to the outer environment, liquid sweat is absorbed from the skin in the garment (Fan 2005). When the textile fibres come in contact with liquid water the water molecules wet the surface of the fabric, before being transported into and then through the inter-fibres pores. At this stage, the solid interface of the fibres, characterized by air, is replaced by a liquid interface (sweat) in a process called wetting (Kissa 1996). When the fibres and the capillary spaces (between the fibres) are wetted with a liquid, a capillary flow starts to occur. The ability to sustain this capillary flow is defined as wickability. Therefore, when a porous material, such as a textile, is placed in contact with a liquid, after wetting, a spontaneous uptake of liquid occurs, in a process called wicking. Wicking is the ability of a fabric to transport liquid sweat. The uptake of liquid is defined as 'spontaneous' because the movement of liquid takes place against zero or negative liquid-head pressure gradient (Miller and Tyomkin 1984). The spontaneous water uptake in the plane of the fabric is always called wicking and is referred to as 'in-plane wicking' or 'horizontal wicking', whereas the liquid movement perpendicular to the plane of the fabrics it is termed ‘transplanar uptake’ (Miller and Tyomkin 1984), ‘transplanar flow’, ‘demand wettability’ or ‘transplanar wicking’ (Rossi et al., 2011).

When the first synthetic fabrics became available in the market, Fourt et al. (1951) compared the water absorption and drying properties of synthetic fibres with conventional natural fibres, i.e. wool and cotton. It was observed that regardless of fibre content, all fabrics picked-up water and the time they took to dry was proportional to the amount of water they initially picked-up. In support, forty-five years later, Crow and Osczevski (1998) found that the amount of water picked up by fabrics, different in fibre content, was correlated to their thickness ($r = 0.92$). Additionally, a strong positive correlation ($r = 0.98$) was observed between the amount of water initially present in these fabrics and the time for them to dry; the correlation was independent of fibre type. Finally, it was indicated that fabrics with open-structure picked up less water, due to their lower capillary volume.

The common notion that natural fibres absorb more water than synthetic ones, could be explained in light of their higher regain, i.e. they can absorb more moisture vapour than synthetic fibres. Nevertheless, Crow and Osczevski (1998) found no correlation between fibre regain and the amount of liquid absorbed by the fabrics, both natural and synthetic. In this regard, Yoo and Barker (2004) indicated that the difference between hydrophilic (in this case natural) and hydrophobic (in this case synthetic) fabrics is in the rate of water absorption, but the total amount of liquid absorbed does not change in relation to the fibre type.

Later on, Jeon et al. (2011a) compared the absorption behaviour of four fabrics with different fibre content and moisture behaviour: cotton, polyester, high-performance polyester (micro-channel cross section, to improve wicking) and high-performance polyester/polypropylene blend (double-sided fabric with propylene skin-side and polyester outside). The results indicated that cotton absorbed water faster than the other fabrics at the moment of the initial contact with the liquid; however, the total absorption capacity was the lowest. By contrast, the polyester/polypropylene fabric showed the slowest initial absorption rate, but the largest total absorption capacity. Finally, the total absorption capacity of the polyester and high-performance polyester fabrics was in between that of cotton and polyester/polypropylene materials. In the experiment, the absorption behaviour of the fabrics was tested by using a demand wettability test, in which generally the total absorption capacity is related to the fabric density (the weight per volume of material including voids, $g \cdot cm^{-3}$). In fact, the cotton fabric had the highest apparent density, followed by polyester, high-performance polyester and polyester/polypropylene. Therefore, in this particular condition, given that fabric thickness was almost the same (0.60 ± 0.03 mm) between the four materials, the absorbency capacity was closely related to fabric weight. Furthermore, the initial absorption rate was highly affected by absorbency time (time taken for a drop of water, delivered onto the fabric, to be completely absorbed), the latter determined by the hydrophilicity and surface properties of the fabrics (Yoo and Barker 2004).

In summary, material-based studies have demonstrated that the amount of water absorbed is mainly dependent on fabric thickness and, in the case of open-structure fabrics, on the capillary volume, fabric density and also weight. This suggests that structural and construction properties play a more important role than fibre type in fabrics in steady-state of absorption. However, in transient conditions fabric hydrophilicity and the impact that this has on absorption rate and related drying time might play a more important role.

1.5.7 Air permeability & ventilation

The produced sweat can also be ventilated directly from the clothing microclimate through the fabric material (air permeability; breathability) or clothing openings, gaps and vents (clothing ventilation). At material level, air permeability is defined, as the velocity of an air flow passing perpendicularly through a test specimen under a specific condition of the test area, pressure drop and time (BS EN ISO 9137: 1995). When using highly air permeable and/or highly ventilated garments, evaporative heat loss will be higher than expected and thermal insulation will be lower than expected. Ventilation rate together with clothing thermal insulation are two important parameters affecting heat and moisture transport properties (Havenith et al. 1990), thus affecting thermal and moisture comfort. Ventilation features are often suggested as a possible solution to the problem of changing activity intensity (and thus metabolic heat production), which requires a reduction in clothing thermal insulation to maintain thermal balance and comfort (Morrissey & Rossi 2013). A number of studies have been carried out to investigate the impact of wind and garment apertures on clothing thermal insulation and ventilation rate. Havenith et al. (1990; 2007) found that wind significantly impacts clothing ventilation rate and later on, Havenith & Nilsson (2004) corrected the thermal insulation model according to the effect of wind and walking.

1.5.8 Drying property

The process of vapour and liquid moisture exchange between the textile fibres and the surrounding environment is described by the drying behaviour of fabrics. The process involves three distinct stages (Lyons and Vollers 1971). In the first stage, a wet fabric adjusts its temperature and the moisture starts to flow towards its surrounding environment. The second stage is a 'constant drying rate' period, in which the drying rate remains constant as the rates of heat transfer and vaporisation reach equilibrium. At this stage, liquid moisture moves within the fabric to maintain saturation at the fabric surface. In a third stage, a 'declined drying state' occurs. Specifically, the flow of moisture to the fabric surface becomes insufficient to maintain saturation and the plane of evaporation moves into the fabric. At this point, the fibres begin to desorb moisture until equilibrium between the fabric and the surrounding environment is achieved. Figure 15 illustrates the drying behaviour of wool and polyester fabrics, at 25 °C and 25 % rH (Li et al. 1995). The difference between the two fabrics is that the constant rate period by evaporation is prolonged for the polyester as its saturation and moisture content is below 1 %, whilst the declined drying rate phase is prolonged in the wool material, since wool presents much higher water saturation (up to 36 %).

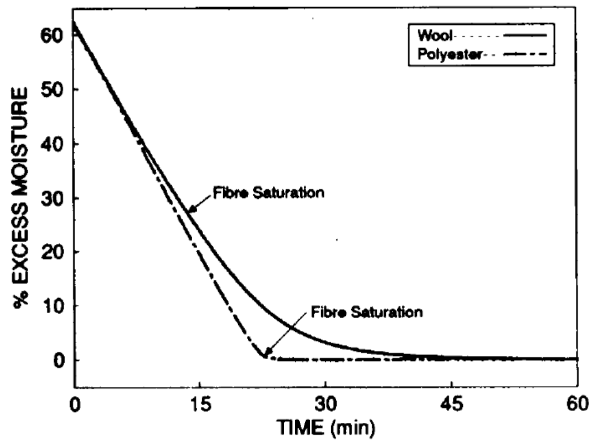

Figure 15 Changes in water content of wet fabrics during drying at 25°C. From Li et al. 1995.

In addition, in Figure 16 fabric temperature during the drying process is illustrated. When the water content of fabrics is above their saturation regain, the temperature of the two fabrics is the same and below ambient temperature, since the dominant process occurring is the evaporation of free water. As water content in both fabrics starts to approach the corresponding equilibrium regains, the temperature of the fabrics starts to rise until all the excess moisture has evaporated and equilibrium is achieved with the surrounding environment. It can be observed that compared to the polyester fabric the wool fabric shows a longer transition period from wet to dry. This reflects the greater moisture sorption capacity of wool and its influence between the fabric and the environment.

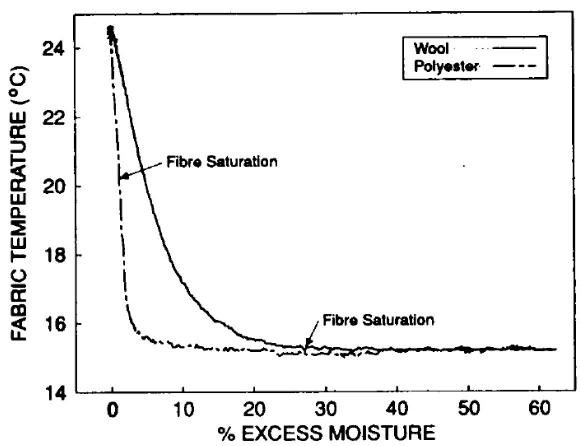

Figure 16 Relation between fabric temperature and excess moisture of wool and polyester fabrics at 25°C and 25% rh. From Li et al. 1995.

1.5.9 Clothing evaluation

The seminal work conducted by Ralph Goldman, to assess clothing properties and its end-performance, includes a multilevel evaluation approach (from Cena and Clark 1981). At the first level, objective test methods are conducted to assess fabric thermal and moisture properties. These instrumental tests are quick, precise and logistically simple to perform. At a second level, full garments are evaluated using thermal manikins, which provide more realistic data as compared to material tests. At level three, clothing is tested using human participants in either controlled laboratory conditions or real-life conditions (field studies). With each incremental level of testing, the yield of scientific information and reproducibility decreases and the cost and number of potential confounding variables increases. In fact, at level three, the evaluation becomes more logistically complex, and drawing conclusion on clothing behaviours, based on fundamental principles, becomes more difficult, due to the multifactorial interaction between environment, human and clothing factors. Nevertheless, only via level three it is possible to obtain information regarding clothing functionality, in relation to human physiological and sensorial responses, as well as consumer's preference in targeted-use conditions.

1.5.10 Level 1 – Material Testing

1.5.10.1 Dry and evaporative heat transfer

The Sweating Guarded Hotplate

The international standard ISO 11092 provides guidelines to measure thermal and water-vapour resistance under steady-state conditions, using the sweating guarded-hotplate.

The apparatus consists of three main components: the measuring unit, with temperature and water supply control (Fig 17), the thermal guard with temperature control (Fig 18) and the test enclosure. The measuring unit presents a metal plate fixed to a conductive metal block (14) containing an electrical heating element (6). For the measurement of water-vapour resistance, the metal plate (1) must be porous. Water is fed to the porous plate (1) from a dosing device (motor-driven burette; 5) by channels machined into the face of the heating element block. Before entering the measuring unit, water is preheated to the temperature of the measuring unit. This is achieved by passing the water through tubes in the thermal guard before it enters the measuring unit. The temperature controller (3) and the temperature sensor of the measuring unit (2) maintain the temperature of the measuring unit constant and the heating power is measured by means of a suitable device (4).

The thermal guard (8) is made of a material with high thermal conductivity, typically metal, and contains electrical heating elements. Its aim is to prevent heat leakage from the sides and bottom of the measuring unit by removing the temperature gradient between the measuring unit and its sides as well as base. It surrounds the measuring unit and is located within an opening in a measurable table (11). To form moisture guard the thermal guard is fitted with a porous plate and water-dosing system similar to that of the measuring unit.

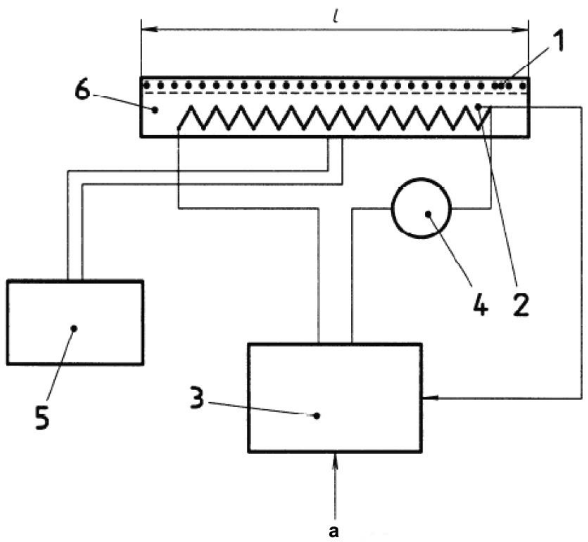

Figure 17-Measuring unit with temperature and water supply control. 1 metal plate; 2 temperature sensor; 3 temperature controller; 4 heating-power measuring device; 5 water-dosing service; 6 metal block with heating element. From BS EN ISO 11092:2014.

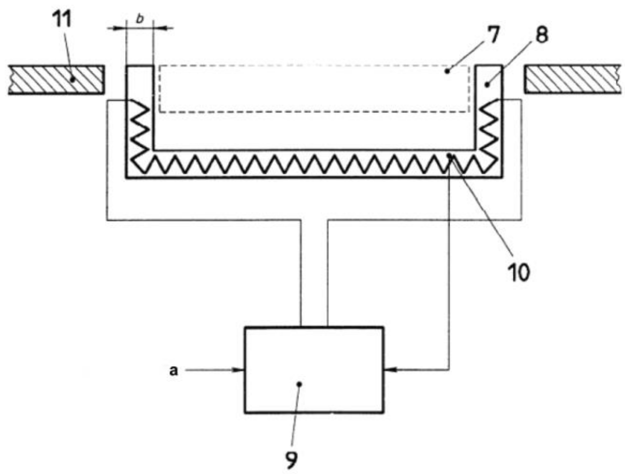

Figure 18-Thermal guard with temperature controller. 7 measuring unit (according to Fig 1); 8 thermal guard; 9 temperature controller (according to fig 1); 10 temperature sensor (according to fig 1); 11 measuring table. From ISO 11092.

The measuring unit and the thermal guard are built into a test enclosure, in which the ambient temperature and humidity are controlled.

The principle of this test for the determination of thermal resistance (R_{ct}) is to measure the heat flux through the test specimen after reaching steady-state conditions. R_{ct} of a material is determined by subtracting the thermal resistance of the boundary air layer above the surface of the test apparatus from that of the test specimen plus the boundary layer, both measured at the same conditions. The temperature of the measuring unit (T_m) is typically set at 35 °C and the air temperature (T_a) at 20° C with 65% RH and air speed at 1 m·s^{-1}. R_{ct} is calculated as follow:

$$\mathrm{R}_{ct} = \frac{(T_{m-}T_a)}{H - \Delta H_c} - \mathrm{R}_{ct0}$$

Were, H is the heating power supplied to the measuring unit in watts; R_{ct0} is the resistance of the boundary layer layer measured with a bare plate (in square metres kelvin per watt); and ΔH_c is a correction term.

The bare plate resistance (R_{ct0}) is determined as:

$$\mathrm{R}_{ct0} = \frac{(T_{m-}T_a) \cdot A}{H - \Delta H_c}$$

Where, A is the area of the measuring unit in square metres.

For the determination of the bare plate resistance the temperature of the measuring unit (T_m) is maintained at 35°C and the air temperature T_a at 20 °C with 65% RH and air speed at 1 $m \cdot s^{-1}$.

For the determination of water-vapour resistance (R_{et}), the electrically heated porous plate is covered by a water-vapour permeable but liquid impermeable membrane. The water fed to the heated plate evaporates and passes through the membrane as vapour and no liquid water contacts the specimen. With the test specimen put on the membrane, the heat flux necessary to maintain a constant temperature at the plate is a measure of the rate of water evaporation, and from this, the water-vapour resistance of the test specimen is determined. The temperature of both measuring unit (T_m) and the air (T_a) is set to 35 °C (no gradient, therefore no dry heat loss) with 40% RH, corresponding to a water-vapour partial pressure difference of 2,250 p_a. The water-vapour pressure p_m, directly at the surface of the measuring unit, can be assumed equal to the saturation vapour pressure at the temperature of this surface, i.e. 5,620 P_a. Air speed is set to 1 $m \cdot s^{-1}$. This isothermal condition is to prevent water-vapour condensation within the test specimen and also to prevent dry heat loss, due to the presence of a thermal gradient. R_{et} is calculated as follow:

$$\mathrm{R}_{et} = \frac{(p_m - p_a)}{H - \Delta H_e} - \mathrm{R}_{et0}$$

Were, p_m is the saturation water-vapour partial pressure, in pascal, at the surface of the measuring unit at temperature T_m; p_a is the water-vapour partial pressure, in pascal, of the air in the test enclosure at temperature T_a; H is the heating power supplied to the measuring unit is watts; R_{et0} is the apparatus constant (square metres pascal per watt); ΔH_e is a correction term for heating power.

R_{et0} is determined as follow:

$$\mathrm{R}_{et0} = \frac{(p_m - p_a) \cdot A}{H - \Delta H_e}$$

Were, A is the area of the measuring unit in square metres.

The temperature of both measuring unit (T_m) and the air (T_a) is set to 35 °C with 40% RH and air speed at 1 m·s^{-1}

The sweating hot plate measurements can be also conducted in accordance with the ASTM F1868. The difference between ISO 11092 and ASTW F1868 is the environmental conditions used; otherwise, the test is performed in the same way. Specifically, in ASTM F1868, for the termination of R_{ct} the temperature of the plate is maintained at 35 °C, air temperature is set at 25 °C, with 65% RH and air speed at 1 m·s^{-1}.

1.5.10.2 Water vapour transfer methods

Desiccant Inverted Cup Test

The standard BS EN ISO 15496:2004 provides a detailed description of the Desiccant Inverted Cup Test, applied to measure water vapour permeability (WVP) of fabrics (Fig 19). In this test, the specimen is placed, together with a waterproof but highly water-vapour permeable hydrophobic membrane, on a ring holder and then put into a water bath so that the membrane is in contact with the water and is left in there for 15 min. A frame, consisting of two plates, separated by spacers, supports the specimen holders in the water. A cup containing saturated potassium acetate solution, creating a relative humidity of about 23% at the specimen's upper face and covered with a second piece of the same membrane, is weighed and then inverted above the specimen in the ring holder, so that the membrane is in contact with the specimen. At this point a net transfer of water vapour through the specimen from the water side to the cup will start to occur. After 15 min the cup is taken off and re-weighted. At the same time, the same test without the fabric specimen is conducted to determine the water vapour permeability of two membranes and the apparatus water vapour permeability. At this point, water vapour permeability of the specimen is calculated, correcting for the influence of the two membranes.

Water vapour permeability is measured according to the following equations:

$$\Delta_m = m_{15} - m_0$$

Were, Δ_m is the change is mass (g) of the measuring cup during the period Δ_t (h); m_0 is the mass of the cup before the start of the test; m_{15} is the mass of the cup after 15 min.

At this point the water vapour permeability of the apparatus WVP_{app} ($g/m^2 \cdot Pa \cdot h$) is measured according to:

$$WVP_{app} = \frac{\Delta_{mapp}}{a * \Delta_p * \Delta_t}$$

Were, Δ_{mapp} is the change in mass (g) of the measuring cup during the period Δ_t (h); *a* is the area op the measuring cup; Δp is the partial vapour pressure difference across the specimen; Δt is the measuring time.

Finally, water vapour permeability of the test specimen can be measured according to:

$$WVP = \left(\frac{a * \Delta_p * \Delta_t}{\Delta_m} - \frac{1}{WVP_{app}}\right)^{-1}$$

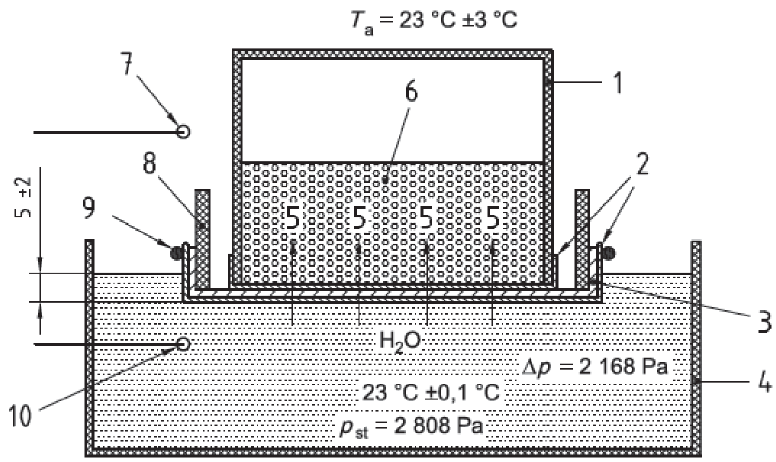

Figure 19-Schematic test arrangement for the desiccant cup method. 1 measuring cup; 2 membranes; 3 textile specimen; 4 water bath; 5 water vapour; 6 saturated potassium acetate solution; 7 temperature sensor for ambient temperature; 8 specimen holder; 9 rubber ring; 10 temperature sensor. From BS EN ISO 15496:2004.

Upright Cup Test

Water vapour transmission of materials can be also measured according to ASTM E96 1999, using the Upright Cup Method. In this test, a shallow cup is filled with 100 mL of distilled water and a circular textile sample is put on top of the cup, covered with a gasket and clamping into its position (Fig 20). The cup assembly is placed in an environmental chamber where air temperature is set to 23 °C, RH to 50% and air velocity maintained at 2.8 $m \cdot s^{-1}$. The cup assembly is weighed periodically throughout one day and water vapour transmission rate (WVT, $g \cdot m^{-2} \cdot day^{-1}$) is calculated according to:

$$WVT = \frac{G * 24}{t * A}$$

Were, G is the mass change of the sample (g); t is the time during which G occurs (h); A is the area of the tested sample (m^2).

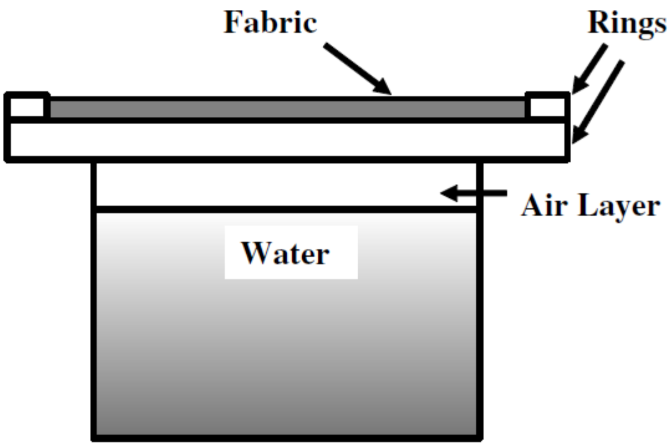

Figure 20-Upright cup assembly. From ASTM E96 1999

Inverted Cup Test

Another method to measure water vapour transmission rate of fabrics is the Inverted Cup Method (Fig 21), according to ASTM E96 1999. This test is very similar to the Upright Cup test and same environmental conditions are applied (air temperature 23° C, RH 50% and air velocity 2.8 $m \cdot s^{-1}$). As the name of the test suggests, the cup is positioned in an inverted position on the upper deck, the fabric sample is positioned over the mouth of the cup and to prevent the water in the cup from wetting the specimen, a hydrophobic membrane is sealed over the mouth of the cup (positioned between the fabric sample and the cup). Differently from the upright test, in the inverted test water is 'in contact' with the fabric, even if a membrane physically separates the liquid water from the specimen. The cup assembly is weighed periodically throughout one day and the calculation of water vapour transmission rate (WVT, $g \cdot m^{-2} \cdot day^{-1}$) is the same as that for the upright cup test.

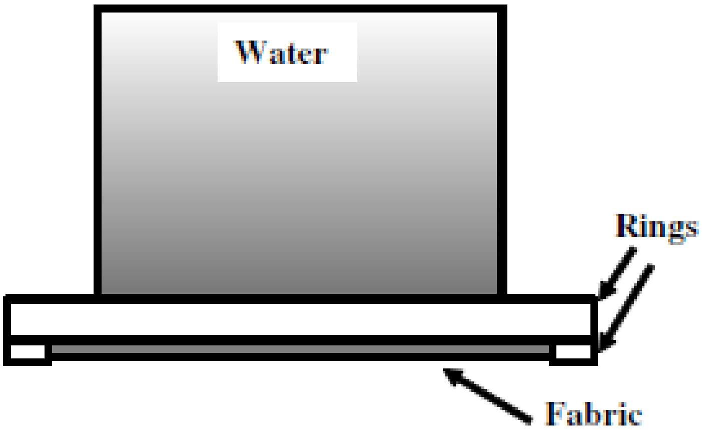

Figure 21-Inverted cup assembly. From ASTM E96 1999

1.5.10.3 Liquid water transfer

In this paragraph, various objective test methods to evaluate liquid moisture absorption and transfer properties of fabrics are reviewed. According to the technology adopted, these methods are classified in gravimetric/volumetric, observational, optical, electrical and temperature-based (Fig 22). The related properties measured are water absorption, vertical and horizontal wicking, absorption capacity and moisture content.

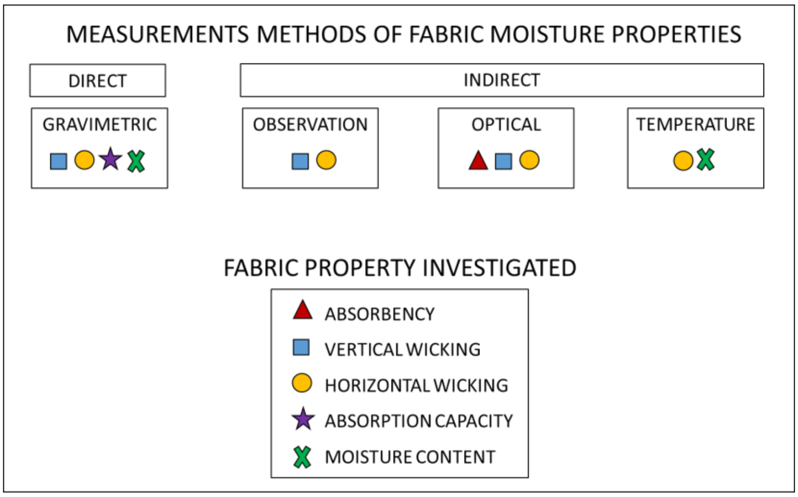

Figure 22 Diagram representing the measurement methods to measure fabric moisture absorption and transport properties.

1.5.10.4 Gravimetric/volumetric methods

Gravimetric/volumetric methods include various tests to directly measure liquid water retention and transport properties of fabrics. The principle consists of measuring the fabric before in dry state and after in wet state and, based on weight changes, moisture content/transfer can be calculated.

Vertical wicking

In the vertical wicking test, a fabric strip is suspended vertically with one end into a beaker of water and the other end is fixed to the clamp of a tensometer. The tensometer records the height reached by the wicked water and is related to time. By using a microbalance and a data acquisition computer, change in mass of the fabric (which increases as the liquid wicks into the sample) is recorded versus time (Hsieh et al. 1992; Ghali et al. 1994; Hong and Kim 2007). This method is easy and simple to perform, however, one of the main limitations is that the water evaporation from the fabric, during the wicking and measurement process can affect the end results. In this regard, a solution could be to test the fabric in a volumetric flask or in a controlled sealed environment (Ghali et al. 1994; Hong and Kim 2007). In order to allow measurement of the amount of liquid absorbed at different height level within the fabric, Ghali et al. (1994), developed an advanced version of the test. In this test, the fabric strip is marked at regular intervals. The fabric is then suspended with one end dipping in a water reservoir. At the end of the test, the specimen is cut across the marked lines and each cut piece is weighted. The degree of saturation of each piece is then calculated. In order to minimize water evaporation during the measurement of fabric vertical wicking, Hong & Kim (2007) developed a similar test where the strip of fabric is clamped, under controlled pressure, between two transparent acrylic plates with the end of the fabric (1 mm) immersed into a liquid. In this setting, the mass of the water absorbed is recorded against time. The limitation of this method is that the water may wick through the space between the fabric and the acrylic plate, which might overestimate the wicking ability of the fabric itself.

Horizontal wicking

In the horizontal wicking test, a fabric is placed flat on a porous plate while water is supplied from beneath (Fig 23). Water can be supplied to the porous plate with a tube connected to a capillary tube containing a meniscus (Harnett and Mehta 1984). By recording at progressive time intervals the position of the meniscus along the horizontal capillary tube, the water uptake of the fabric (which depends on its wicking ability) is measured (as the fabric absorbs water the meniscus moves towards the test fabric). In this volumetric analysis method, the absorption rate of the fabric is calculated by knowing the diameter of the capillary tube and the distance covered by the meniscus. However, this test presents some limitations. First of all, for highly absorptive fabrics, the observation of the meniscus position in the capillary tube may not yield a sufficiently sensitive measurement, as the great absorption property might result in a fast reduction of the meniscus length. Additionally, the resistance to the water flow, offered by the capillary tube remaining filled with water, decreases during the test, as water is absorbed by the tested fabric. In this regard, the unstable resistance of the flow can affect the accuracy of the test. In a similar experimental setup absorption capacity and/or rate can be measured, using the gravimetric absorption testing system (GATS) (Yoo and Barker 2004; Tang et al. 2014b). In this test, the plate can contain a small hole or can consist of a porous plate. To improve repeatability of the test, water is supplied at a constant rate, e.g. 10 $mL \cdot h^{-1}$ (Tang et al. 2014b). To simultaneously, measure horizontal wicking using an optical method, a camera can be positioned at the top of the setup, to capture the image of the wetted sample and from the pixel of the wetted area the water spreading area can be calculated (Tang et al. 2014b).

In order to ensure good even contact between the fabric and the plate, in these experimental setups an external load is applied to the fabrics. However, while it is important to ensure good fabric-to-plate contact, the external load can result in high pressure and compress the fabric, which does not occur in real wear conditions.

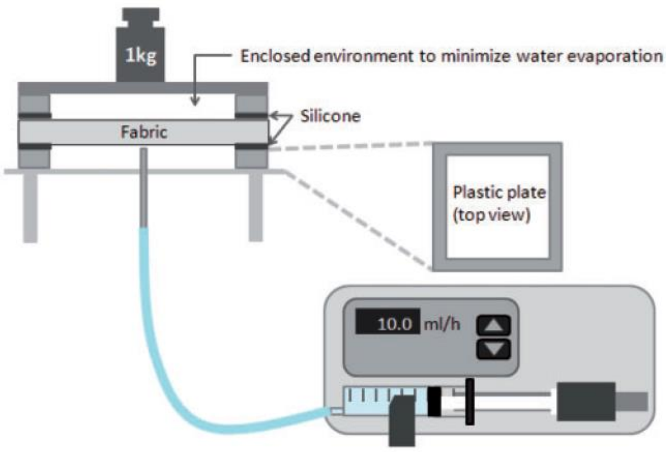

Figure 23 Schematic drawing of horizontal wicking test. From Tang et al., 2014.

Absorption capacity

In this test, a fabric is put into a tank of water and it is kept in there for 5 min in order to allow it to sink completely into the water. After that, the fabric is taken out with tweezers and hung vertically onto a rod until there is no water dripping within a 30-seconds interval (Tang et al. 2014a). The water gain in the fabric is measured, from dry and wet weight, and expressed as mass of water gain per unit area of fabric ($g \cdot cm^{-2}$).

1.5.10.5 Observational methods

Observation-based methods are commonly applied to measure fabric absorbency as well as wicking properties.

Absorbency and Saturation

Currently there are two observational-based standard tests to measure fabric absorbency: AATCC 79-2014 and BS EN ISO 4554:1970. The main purpose of these tests is to simulate sweat spreading across the fabric when it comes in contact with the skin. Specifically, in both tests, a drop of water is delivered at a fixed distance onto the fabric. The time taken for the reflection of the liquid surface to disappear is taken as a measure of the absorbency of the fabric. The shorter the time, the higher is fabric absorbency. For fabrics with a very high absorbency, i.e. when the deionised water takes less than two seconds to disappear, a 50 % sucrose solution should be used (BS EN ISO 4554 1970). Measurements of the wetted fabric area can be conducted by placing a graph paper beneath the fabric and manually tracing with a pen the area of water spread (Sampath et al. 2011b). In order to gather more information regarding wicking properties of fabrics, when a certain amount of liquid is delivered to the fabric, fabric moisture saturation can also be measured (De Boer 1980; Sampath et al. 2011a). Moisture saturation of the fabric is an important parameter to take into account when studying clothing comfort and it can be calculated by considering the mass of the liquid absorbed as the percentage of the dry weight of a certain fabric area. By applying a similar set-up it is also possible to measure fabric saturation, by continuously adding water to the fabric at a certain rate, until the fabric cannot absorb any more water (Sampath et al. 2011b).

The observational-based tests above reported typically applied to measure absorbency and fabric saturation, are simple to conduct, do not require expensive equipment and are quick to perform. However, the observational nature of the test can reduce its accuracy. For instance, the determination of the end-point of the test is prone to subjective individual variations. Additionally, for fabrics with very high absorbency, it becomes difficult for the investigator to make fast measurements. Furthermore, the use of sucrose solution for fabrics with high absorbency has some critical implications. For instance, the presence of sugar can change the viscosity and the surface tension of the liquid, this ultimately affecting water kinetics, which is relevant for wear comfort related-assessments. Therefore, when fabric absorbency is quite high, a different testing methodology should be applied rather than just replacing the liquid used for the test.

Vertical wicking

There are various test methods that apply an observation principle to measure fabric vertical wicking. The procedure involves suspending a strip of fabric with its lower end immersed into a water reservoir. The height of the water reached in the fabric is then measured after a fixed time. Alternatively, it is possible to focus on the time taken for the liquid to reach a specific distance within the fabric. This could allow a rough estimation of the time-dependency of the wicking property of the tested fabric. This testing set-up, used to measure vertical wicking is currently adopted by two standard test method: BS 3424 Testing coated fabrics – Part 18: Method 21A Methods for Determination of Resistance to Wicking (1986) and DIN 53924 Determination of the Rate of Absorption of Water by Textile Materials (Deutsches Institut für Normung eV DIN 53924 1997). The method BS 3424 Testing coated fabrics, is indeed intended for testing coated fabrics, which have a very low/slow wicking behaviour. For this reason, the standard recommends long test duration of 24 hours. On the other hand, the standard DIN 53924 mainly targets fabrics with rapid wicking ability, therefore a much shorter time (5 minutes) is recommended.

The vertical wicking tests that adopt the observational-based method are easier to perform than the gravimetric ones. In fact, the observation-based tests do not even require the use of specific equipment, such as balances. One of the limitations that the vertical wicking tests have, both gravimetric and observational ones, is that the water uptake in a vertically suspended fabric shows a gradient distribution pattern. The latter consists of a saturated zone near the water-fabric interface followed by a distribution zone; therefore water spreading across the material is non-uniform. For observation-based tests, the latter makes difficult to measure the wetted area, since for some fabrics, such as thick or composite materials, the front of the liquid spread, in the area where the liquid diffuses, might not be easy to detect. This becomes even more complicated for dark coloured fabrics. The issue could be solved by adding dye to the water, however, in some cases water can migrate faster than the dye, leaving the problem unsolved and also affecting the measurements. Another problem is related to the fact that only wicking at the surface of the fabric can be measured, while information regarding wicking speed at the intra-fibre and inter-fibre space is unknown. Therefore, that means that the liquid detected at the front of the fabric is not always related to the volume of the liquid wetting the whole material. This issue becomes more critical for fabrics with different face and back side, for thicker fabrics and fabrics made of multiple plies. Finally, the direction of the water spreading does not simulate wear conditions since water transport in clothing is generally transplanar to the fabric plane.

Horizontal wicking

The standard AATCC 198 horizontal wicking of textiles (American Association of Textile Chemists and Colorists AATCC Test Method 198 2013) adopts the observational method to assess the ability of horizontally aligned fabrics to transport liquid along and through them. The standard prescribes to mark in the middle of the fabric sample a circle of 100 mm and to deliver a 1 mL of liquid from a burette or electronic pipette, from a height of 10 mm, onto the centre of the marked circle. The test is completed when the liquid reaches the borders of the marked circle and the duration to achieve this is recorded. The distance reached by the liquid, along the lengthwise and widthwise directions of the fabric is then measured and the spread area per unit time is calculated as a measure of horizontal wicking ability of the fabric.

As the observational vertical wicking tests, the observational horizontal wicking tests are simple to perform and do not require the use of specific equipment. However, the test is not suitable for dark coloured fabrics, and can only be performed on fabrics that can hold the full amount of added liquid without pooling the water on the surface or dripping.

Sink test

In the sink test a fabric sample is put onto the surface of a liquid contained in a water tank. The time for the fabric to sink completely into the liquid is then measured and is used as measure of fabric hydrophilicity. The shorter the sinking time, the higher the hydrophilicity (ISO 9073-6, 2000, Test method for non-wovens).

1.5.10.6 Optical method

Contact angle

The contact angle test adopts an optical method to determine the wettability of fabrics. In this test the angle exhibited by a liquid drop rested on a solid surface is considered (Tang et al. 2014). This angle is obtained by tracing the tangent of the liquid-vapour interface and solid-liquid interface (Fig 24-a). The image is captured by a goniometer (Fig 24-b) which is equipped with a three-axis stage with fine and coarse adjustment, a modular levelling stage, a micrometre-driven syringe and a video microscope. The volume of water applied is strictly controlled. Using the video microscope the images of the drop are recorded and, by using a special algorithm in the software, the drop boundary can be defined. The larger the contact angle the lower the hydrophilicity of the materials tested. A contact angle lower than 90° shows that there is an affinity between the liquid and the solid material, whereas when the angle exceeds 90° there is a repulsion between liquid and solid phase. The duration of the test is short and it can be applied to slow and not–absorbent fabrics. However there are some difficulties with high-absorbency fabrics, because the immediate absorption of water into the fabrics results in a rapid change of the contact angle. Contact angle measurement assumes the presence of a smooth textile surface, which is not always the case. In fact, it was demonstrated that different fabric geometry and roughness of the surface may yield different ‘apparent’ wetting contact angles even though the fibre content was identical (Patnaik et al. 2006). Additionally, the velocity of the water injection, as well as the tangent line determination is difficult to standardise and the repeatability and reliability of the results rely on the consistency of the operator.

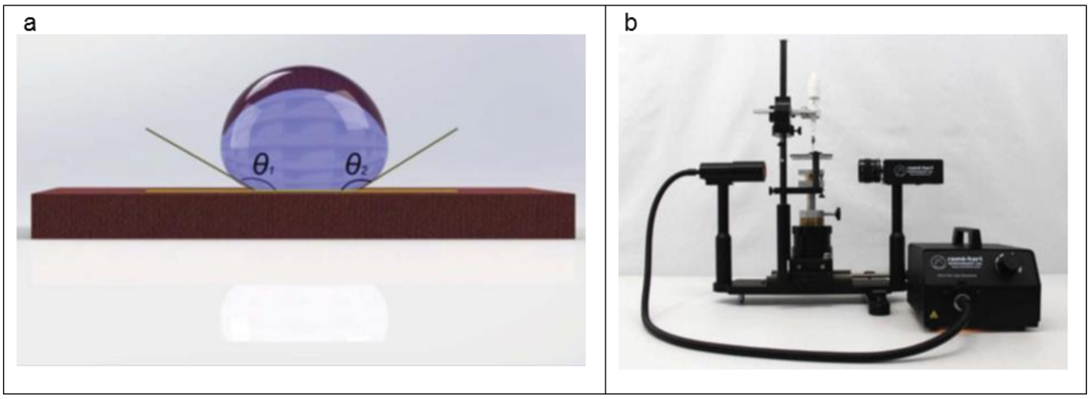

Figure 24 (a) Tangential lines at the borders of the water drop. (b) Contact Angle Goniometer/Tensiometer (rame-hart Model 260). From Tang et al. 2014.

Vertical wicking

Using an image-analysis technique it is possible to detect the increase in fabric wicking over time (Zhuang et al. 2002). As in a typical vertical wicking test, the fabric sample is suspended with its lower end contacting the liquid contained in a tank. Opposite the fabric sample is placed a camera which can capture water spreading at regular intervals. This is achieved by installing the camera on a shaft connected to a step motor to automatically track the location of the liquid. The greatest advantage of this optical wicking test, as compared to the gravimetric and observational ones, is that the manual and subjective operation in the process is minimised, the latter improving the test consistency. Nevertheless, although in this specific set-up the time-dependency of the wicking behaviour can be measured, the previously mentioned fundamental limitations characterising vertical wicking testing remain.

Horizontal wicking

The optical method can also be used to measure the spreading area of liquid in a textile placed horizontally on a flat plane. In this experimental set-up developed by Kissa (1996), a drop of water is injected onto a fabric sample, using a hypodermic needle. A timer is positioned close to the sample, and fabric spreading area, as well as the reading on the timer, is recorded at regular intervals, using an instant-picture camera, held in a fixed position. In order to reduce variations, the injection of the water should not be performed manually, as in the case of this test. This limitation can be solved using a flow-rate controller or a control injection speed. To improve the accuracy of the measurements a digital camera together with a video camera should be used instead (Tang et al. 2014b). Another drawback is that the test is not suitable for fabrics with poor absorbency since the injected water will drop off the poor-absorbing material immediately.

The Absorbency Testing System

The Absorbency Testing System (ATS-600; Sherwook instrument, Inc.) is an optical device developed to measure absorption properties of various materials, including paper and non-woven. The apparatus can measure absorption rate, absorption capacity and horizontal wicking. The device presents a platform where the fabric sample is placed horizontally. The platform is made of monofilament mesh to enable the measurement of intrinsic absorption properties of the material. Water is supplied from underneath. The device also presents an optical sensor and a motorised syringe used to maintain a constant fluid level at a pre-set differential head-pressure during the test. The optical device tracks water content in the water reservoir adopting a volumetric approach. Absorption properties are measure based on time and fluid displaced from the water reservoir.

Change in colour depth

Using an optical approach, the amount of water absorbed by a fabric can be estimated by measuring the differences in the depth of the fabric colour between dry and wet state (Lee et al. 2001), using a spectrophotomer (ColorEye 3000, ICS-Texicon Co., USA). The principle of this approach is that the colour of a fabric in wet state appears darker than in dry state. A study investigated the relation between moisture content and colour depth of fabrics, wetted between 10% and 90% of their maximum absorption capacity (Lee et al. 2001). A linear relationship was observed between absorption weight and the reflective characteristics (lightness and colour difference) of the studied fabrics. Nevertheless, although this test can be suitable for dark-coloured fabrics, the degree of colour change can be affected by fibre content, yarn type and fabric construction, even when the same water content is applied.

1.5.10.7 Electrical methods

When water comes in contact with a textile material, the electrical properties of the material change. These changes can be used to indirectly measure moisture absorption and distribution in fabrics. The electric method allows measurements of moisture absorption and transport properties in fabrics where other methods are unsuccessful. For instance, the electrical approach is excellent for dark-coloured fabrics, where the observational-based wicking and absorption test fail.

Automated wettability tester

The electrical method can be applied to measure fabric absorbency. The experimental set up is similar to an absorbency test that adopts the observational-based method (De Boer 1980; Sampath et al. 2011a). However, in this test, the fabric presents four electrodes and the time that the water takes to spread and reach the sensors is recorded automatically (Tang et al. 2014b). Since the end-point of the test is determined automatically, rather than manually, the reliability of the test is improved.

Moisture Management Tester

Dynamic liquid moisture management properties of textile materials can be characterised using the Moisture Management Tester (MMT) (Hu 2005), according to AATCC Test Method 195-2011. The principle of the test is to measure changes in the electrical resistance of the two textile sides after being wetted. The electrical resistance of a dry textile is usually very large, however, when moisture is transported in a fabric its electrical resistance will drop. Changes in resistance depend on the water composition and amount of water; by fixing the water composition the measured changes in fabric resistance will be related to the fabric water content (Li et al. 2002). With regards to the test procedure, a 9 x 9 cm specimen is held flat between an upper and lower sensor at a certain pressure (Fig 25). Both the upper and lower sensors consist of a couple of proximate copper rings (Fig 25). Synthetic sweat (AATCC 15-2013) is pumped for 60 seconds into a simulated 'sweat gland' (Fig 25) and from this point, it is introduced onto the top fabric surface (fabric skin side, in contact with the upper sensor). The system is connected to a computer that dynamically records the resistance change between each couple of proximate metal rings at the top and lower sensors. After contacting the top fabric surface, the solution will transfer in three dimensions, it will: 1) spread outward on the top surface, 2) move from the top towards the bottom surface, 3) spread outward on the bottom surface. The resistance between each couple of metal rings will decrease because the solution can conduct electricity when it contacts the area surrounded by the two proximate metal rings.

Water contents versus time of both fabric top (skin) and bottom (outer) surfaces are recorded and from these, a number set of indices are derived in order to determine fabric moisture management properties. The indices are:

- Wetting time top (WT_t) and bottom (WT_b) is the time in seconds (s) required to wet a fabric after the test is started (time required to contact the first inner ring).
- Maximum absorption rate is the maximum rate at which liquid is absorbed (% of water per second; $\%\cdot s^{-1}$) for the top (MAR_t) and bottom (MAR_b) textile surface, during the initial change of fabric water content during the test (after the contact with the firs ring).
- Maximum wetted radius is defined as the maximum wetted ring radius (mm) of the wetted circular area measured at the top (MWR_t) and bottom (MWR_b) fabric surface.
- Spreading speed ($mm\cdot s^{-1}$) is the speed of water spreading horizontally across the top (SS_t) and bottom (SS_b) surface from the centre of the fabric where the solution is dropped to both MWR_t and MWR_b, respectively.
- Cumulative one-way transport capacity (OWTC) is the difference in the cumulative moisture content between the top and bottom surface, divided by the total testing time (120 seconds). It indicates the movement of water from the skin to the outer side of the fabric. A negative OWTC indicates that liquid cannot diffuse easily from the next-to-skin fabric surface to the outer surface.

Overall moisture management capacity (OMMC) is an index indicating the overall ability of the fabric to manage moisture and it includes three parameters: maximum absorption rate of the bottom fabric surface (MARb), one-way liquid transport ability (OWTC), and moisture drying speed of the bottom surface, which is assumed to be represented by the maximum spreading speed (MWRb). For the calculation of OMMC, OWTC has the major contribution (Hu 2005). The higher the value of OMMC and the better will be the overall moisture management ability of the fabric.

In comparison to the absorption time of the drop test, specified by AATCC Test Method 79, the MMT is more reliable and can also be used for dark-coloured fabrics or for fabrics in which liquid spreads quickly, since the wetting time is recorded by the electric sensors rather than by observation. However, in this test water is supplied from the top to the fabric and gravitation may pull the droplet down adding to any effects from a purely capillary-action driven system. Additionally, only a limited amount of liquid can be applied to the fabrics, which does not simulate the amount of liquid present on the skin during profuse sweating conditions. Finally, the pin used to apply the voltage presents difficulties in testing conductive materials, coated, laminated or complex fabric constructions. Finally, in the case of long-pile fabrics, there may be problems because the pile yarns do not contact the pin properly.

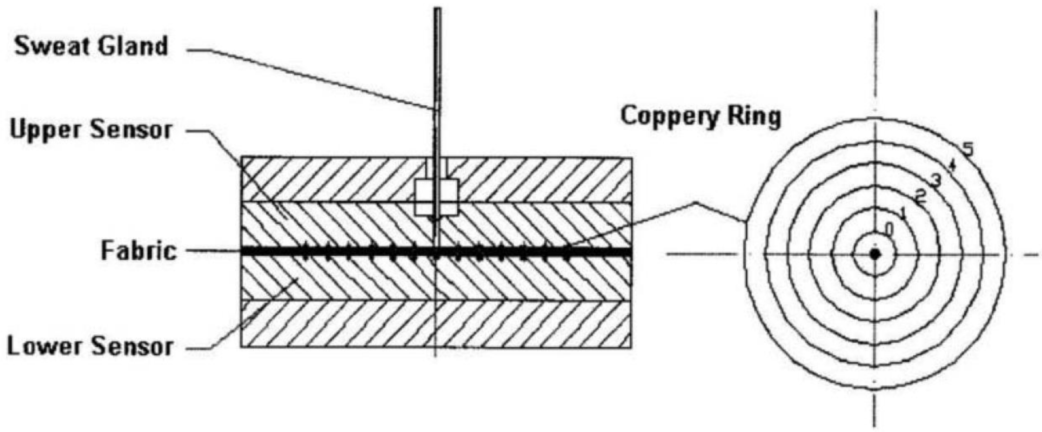

Figure 25-Sketch of the Moisture Management Sensors. From Hu et al., 2005.

1.5.10.8 Temperature-based methods

Temperature-based methods use temperature changes to detect the presence of water in a fabric. The principle is that in a wet fabric, liquid evaporation and increased thermal conductivity will cause decreases in fabric temperature.

Horizontal wicking

The application of thermocouples at different locations and set distances in a fabric allows measurements of in-plane wicking property of fabrics (Zhu and Takatera 2014). In this set-up, water is dropped from the top onto the centre of a fabric. As water spread increases, temperature changes across the fabric occur, which can be detected by the thermocouples. Temperature changes at the various locations (where the thermocouples are placed) are recorded versus time, allowing estimations of in-plane wicking. To obtain good measurements, both lengthwise and widthwise directions within the fabric should be considered. The method allows measurements of wicking behaviours in dark-coloured fabrics. However, apart from spreading time/rate, it does not allow to make estimations with regards to the amount of water absorbed, unless a gravimetric test is integrated.

1.5.10.9 General consideration

Liquid absorption and transfer properties of fabrics are measured and evaluated to ensure human thermal balance and thermal comfort in a wide range of conditions. Benefits and limitations regarding their application are summarised below.

- The gravimetric technique is simple to perform, allows recording of the time-dependency of the property measured in real time. The method does not fail to measure moisture properties of fabrics with irregular spreading behaviour, it is low cost and no specific devices are required, a part from the use of a balance and a timer. On the other hand, the gravimetric method does not provide information regarding the space-dependence of moisture distribution within the textile sample.
- The main advantages of the observation-based technique are that the tests are no expensive and the use of sophisticated apparatus is not required. However, the method is highly prone to subjective errors and variations. Because of this, measurements of materials with high absorbency do not lead to repeatable results.
- Similar to the gravimetric method, the optical method allows recording the time-dependency of the property measured in real time. Additionally, because manual operation is reduced, the testing accuracy is improved.

However, inconsistencies regarding the light properties of the environment in which the test is performed can affect the end results. The tests are not suitable for dark-coloured fabrics and for materials presenting different structures within the same fabric. The uneven spreading of the water makes difficult liquid detection in the fabric, i.e. the exact location where liquid spreading stops. Finally, the spreading area detected at the fabric surface does not necessary related to the volume of the water absorbed.

- The electrical method allows indirect measures of water spreading in fabrics where detection of moisture is difficult if performed with other methods, such as dark-coloured fabrics and fabrics with very high absorbency. Nevertheless, the method is not suitable for conductive materials. The use of sodium chloride as wetting solution can oxidise the electronic parts of the apparatus used, which can cause frequent damage of the device (expensive), as well as reduce the accuracy of the test. Finally, the results may vary in relation to the texture of the fabric, since it can affect the contact between the fabric and the sensors.
- Using a temperature-based method it is possible to record the time-dependency of the property measured in real time. The method is applicable to fabrics with irregular spreading properties. It is versatile, in that it is not affected by the physical appearance of the material tested. The manual manipulation is reduced; this improving the testing accuracy. Nevertheless, fabric roughness can affect the contact between the temperature sensor and the fabric, this affecting the test results. To improve testing accuracy, the climatic environmental conditions should be highly controlled.

In general, when performing a material test to measure liquid moisture absorption and transport, it is necessary to improve testing sensitivity, reproducibility and accuracy. More attention should be paid to the experimental set-up, in order to assess whether it simulates the conditions in which heat and mass transfer occur, i.e. in the clothed body under exercise-induced sweat production conditions. Finally, the data generated by the objective test methods should be validated by specific human tests.

1.5.11 Level 2 – Manikin testing

When textile materials are assembled into clothing, the measurement of thermal insulation and water-vapour resistance is performed with the use of thermal manikins. The first manikin was constructed by the US Army in the early 1940s (Goldman 1974). ‘Charlie 1’ was the first thermal manikin in the world to perform walking action and over the years manikins have been improved.

Thermal manikins can be classified into three categories: (1) static, (2) dynamic, (3) dynamic and sweating. Thermal insulation and evaporative resistance of clothing can be measured by calculating the amount of energy that needs to be transferred to manikin’s body in order to maintain his ‘skin temperature’ constant at given values. The procedure of clothing measurement by means of thermal manikin is standardized in the international standard BS EN ISO 15831:2004 and in ASTM F2370.

Thermal manikins are relatively rare and this makes their use more expensive, compared to textile instrumental evaluations, but, on the plus side, they lead to more practical results. Firstly, given that the garment is fitted to a human-body shape, it is possible to look at the impact that anatomical factors and air gap play on thermal and evaporative resistance of clothing. The set-up also allows measurements of thermal properties of a multilayer clothing system, taking into consideration, skin-to clothing air gap as well as the air gap between clothing layers. With a dynamic manikin (and/or using fans) it is possible to take into account the effect that air movement, due to body motion, has on thermal insulation and evaporative resistance. Additionally, as in cold environments and for protective purposes different fabrics and reinforcements layers are used in the clothing system, results from manikins provide information to optimise materials and clothing design, in order to maximise thermal balance and comfort when wearing the full ensemble. For these reasons, measurements of dry and evaporative heat loss obtained from manikins can give a better representation of body heat loss, compared to material tests.

1.5.12 Level 3 – Human testing

Due to the complex interaction between environmental, human (physiological and perceptual factors) and clothing factors, clothing performance cannot be comprehensively described by material and manikin tests only (You et al., 2002). For this reason, human evaluations are often conducted, with the purpose to investigate the effect of clothing properties and performance on human responses, as well as to validate material tests.

1.5.12.1 Scales of measurement

The direct study of human sensations and perceptions often requires the use of subjective rating scales. There are two main dimensions that comprise all sensations produced by the fabric-skin contact. One dimension is qualitative (descriptive) and relates to the sensory attribute that is perceived e.g. wetness, roughness or stiffness. The other dimension is quantitative and relates to the magnitude of the perceived sensation, e.g. very wet, slightly wet, damp and dry (Cardello et al., 2003). Psychophysical scaling is an example of the second dimension, where participants are asked to give a number based on the characteristics of the investigated object (Li 2001). There are 4 types of scales: nominal (categorization), ordinal (ranking), interval (perception, attitude measures) and ratio (most objective measurement results).

Nominal

Nominal scales are used for labelling variables, without using any quantitative values. Some examples are reported in Figure 26. These scales do not have any numerical significance. A sub-type of nominal scale presenting only two categories (e.g. male/female) is defined dichotomous.

What is your gender
o Male
o Female

What is your hair colour
o Brown
o Blond
o Black
o Grey
o Other

Figure 26 Examples of nominal scales.

Ordinal scales

When using ordinal scales the assessor is asked to rank or compare the fabrics in order. With ordinal scales, in fact, the order of the values is important and significant; however, the difference between values is unknown. Ordinal scales are typically measures of non-numeric concepts, such as sensation or satisfaction. Likert Scales are examples of ordinal scales (Fig 27). The number of categories is usually between 7 and 9, but could be larger. However, when using fewer categories a loss in the discrimination sensitivity could occur as in the scale introduced by Hollies et al. (1979), which only presented 4 categories (4 = partially, 3 = mildly, 2 =definitely and 1 = totally). Another important aspect to consider is the appropriate selection of the descriptor in relation to the corresponding numerical value. For instance, in the example reported in Figure 25, it is not clear what the difference between 'definitely' or 'totally' is. Ordinal scales can be used in paired comparison tests, where two fabrics are given to the assessor at the same time and he/she is required to select one according to the required criteria. Schneider et al. (1996) used the paired comparison test to investigate the coolness sensation of fabrics made from different materials and found that it was effective in differentiating between fabrics with different moisture absorption behaviours. In this way, participants can easily compare two items at a time without the need of memorising what has been rated previously. However, the paired comparison method requires a large number of tests and is time-consuming. Furthermore, it cannot provide an estimate of the magnitude of the perceived difference between samples.

How wet is your skin	
4	partially
3	mildly
2	definitely
1	totally

Figure 27 Example of Likert scale (ordinal scale) introduced by Hollie et al 1979.

Interval scales

Interval scales are numerical scales in which the order, as well as the exact difference between values, is known. The classic example of an interval scale is Celsius temperature or time, since the difference between each value is the same and increments are known, consistent and measurable. Interval scales have been frequently used for psychophysical measurements. For instance, the studies of Plante et al. (1995b), and Kaplan and Okur (2009) were based on the use of interval scales to assess the magnitude of perceived wetness. In this case, the assessors were asked to score their sensation (wetness) along the numerical value continuum by choosing one of several descriptive categories. This method appears simple, versatile and easy for the participants to use. However, as mentioned, interval scales imply that the points on the numbered category represent equal intervals, which is not the case when measuring sensations or perceptions, such as wetness or discomfort, for instance. Another problem is that the participants tend not to use the end-most categories, which can reduce the sensitivity of the measurements.

There are two main kinds of interval rating scales: comparative versus no comparative; this distinction is made based on whether references fabrics are given or not. Plante et al. (1995) for instance adopted a comparative interval rating scales in which dry and very damp fabrics (corresponding to the two extremes) were provided as extreme references. Interval rating scales can be further classified in balance versus unbalance and forced versus unforced. In a balance scale, an equal number of favourable and unfavourable categories are provided and vice versa for the unbalanced scales. In the balance scale, the middle is generally a neutral point and should be used if the assessors feel neutral about a sample. For this reason it is also important to consider the use of forced or unforced scales. In cases in which it is assumed that some assessors may have a lack of knowledge on the matter to be rated, unforced scales should be used, otherwise assessors may often mark the midpoint of the scale (neutral) implying that they have no comments to make; in fact leaving the freedom to give such a response may influence the accuracy of the test.

1.5.12.2 Sensory test method - Psychophysical approach

Psychophysics was introduced by Fechner and it refers to the mathematical relationship between the physical properties of a stimulus (matter) and the sensations evoked (brain process) (Laming 1995).

Threshold experiments

The main concepts of the psychophysics approach are the absolute and the difference threshold. The absolute threshold, or limen from the Latin, (AL), is the minimum value of physical stimulus necessary to evoke a sensation (Sweeney and Branson 1990a). The difference threshold, or limen, (DL) is the minimum amount of stimulus required to produce just a noticeable difference (JND) in the sensation. There are three psychophysical methods for determining AL and DL: the method of limits, the method of adjustment and the method of constant stimuli (Sweeney and Branson 1990a). All three methods ask the participant to simply respond 'yes' or 'no', 'greater' or 'less' to the sensations evoked by different stimuli. Among these, the method of constant stimuli has a higher degree of accuracy, because the stimuli are presented in random order which eliminates constant errors (Jeon et al. 2011). In 1834 Weber proposed that the difference threshold (DL) of a stimulus ($\Delta\varphi$) is a constant fraction of the stimulus intensity (φ). This is known as Weber law and it has been confirmed for a wide range of stimulus intensities and sensory modalities. It is expressed as:

$$\frac{\Delta\phi}{\phi} = K$$

K is the Weber' fraction, which is almost constant; it indicates the human power to detect signals and to discriminate sensations. For examples, it has been indicated that Weber's fraction of touch (heaviness) is 0.02 (arbitrary unit); this means that a 2% change in the heaviness of a particular matter is enough to detect a change.

Sweeney and Branson (1990a) applied the method of constant stimuli to study wetness perception of fabrics. In the study of Jeon et al. (2011), it was demonstrated that the psychophysical method can successfully enable the evaluation of moisture perception of novel functional fabrics where psychological scaling methods have failed. Fechner investigated the relationship between the physical strength of a stimulus and its strength as perceived by humans. Assuming that the Weber's fraction was valid, he proposed that the total change in sensation between two intensities could be indirectly quantified by counting the number of JNDs (Tang et al., 2014). His work was based on the belief that when a JND is added to the stimulus, the psychological sensation increases by a constant size (Jeon et al. 2011). However, nowadays this is not considered an accurate approach, as psychological and physical measures have units of varying sizes (Jeon et al. 2011). Therefore, the JND is a concept describing the difference in sensation given by two stimuli separated by the DL, rather than as a magnitude of a sensation.

Non-threshold experiments

Magnitude estimation is a non-threshold technique. The assessor is first presented with a sample and the magnitude of the sensation of the first sample is either assigned by the investigator or by the assessor. The assessor is then asked to assign a randomly chosen number of the subsequent samples which is proportional to the first sample (Kingdom and Prins 2012). For magnitude estimation approaches, ordinal scales, interval scales or visual analogue scales (VAS) are used.

When using a VAS, participants are asked to score the intensity of a given stimulus by marking a point on a horizontal line. The length of these scales (line) varies between 10 and 15 cm with anchor points at the two extremes. The marks made by the participants on the scale are then converted into numbers by measuring their position on the scale. Ackerley et al. (2012), for example, used a VAS to measure the magnitude of perceived wetness in fabrics.

1.5.12.3 Skin regional studies

Human skin regional studies involve investigations of fabrics on restricted body areas. These investigations typically adopt a mechanistic research approach, focusing on one or a limited number of textile properties and are normally performed under resting conditions.

A number of skin regional studies have been conducted to investigate sensations and perceptions of wet textile materials. Within these studies, differences related to the method used can be observed. Li et al. (1992a) studied wetness perception of wool and polyester materials. Participants were asked to score wetness sensation using a scale ranging from 'definitely dry' to 'very damp'. The fabrics were assessed on the inner forearm and, to prevent any visual influence, participants were blinded. The fabrics were applied in static contact with the skin and the materials were presented in five different wet conditions, according to 0 %, 2%, 4%, 10% and 15% excess of the conditioned weight. Using a similar experimental methodology, Plante et al (1995a) compared wetness perception between fabrics with different fibre composition (wool, wool/polyester blend and polyester). In this case, a 5-point wetness scale, ranging from 'dry' to 'very damp', was used. Furthermore, before the scoring test, reference fabrics, corresponding to the two extreme sensations reported on the scales, were presented to the participants. Sukigara and Niwa (1997) applied a paired comparison method to study wetness sensation of fabrics. The study comprised two different application conditions. In one condition, pre-wetted fabrics were applied in static contact with the skin on the upper back. In another condition, dry fabrics were applied in both static and dynamic contact on the wet skin of the inner forearm. Sadikoglu (2005) measured wetness perception of six fabrics, containing different amounts of superabsorbent fibres and different amount of water were added: 2%, 4%, 6%, 8%, 10%, 15%, 20% and 30% of the conditioned weight. A five-point scale was used (1 definitely dry; 2 barely dry; 3 slightly damp; 4 moderately damp; 5 very damp). The fabrics were applied in static contact with the skin on the inner forearm. A similar approach, but a different scale was used by Yokura and Sikigara (2010). The wetness perception scale presented 5 points with '1 very dry', '2 slightly dry', '3 neutral', '4 slightly wet', '5 very wet'.

Although these skin regional studies apply the same scaling method to assess fabric wetness perception, the scales present different descriptors and level of resolution. Some of these studies included participants of both sexes, other studies only male participants. Furthermore, the experiments were performed in different environmental conditions ranging from 20°C to 35°C and relative humidity from 25% to 75%. The amount of water added to the fabrics varied across studies, as well as the type of contact, i.e. active versus passive. As such, making comparisons between results obtained from different studies seems complex.

One of the main aims of skin regional studies is to explain moisture perceptual responses in relation to results obtained from material tests (moisture transfer and absorption). Jeon et al. (2011a) studied wetness perception of four different fabrics (100 cm^2) made of cotton, polyester, high-performance polyester (micro-channel cross section, to improve wicking) and high-performance polyester/polypropylene blend (double-sided fabric with propylene skin-side and polyester outside). Ten female participants evaluated two levels of fabric wetness: 0.5 and 1.5 mL. The wet fabrics were applied statically on the inner forearm. Within the same fabric, no differences were perceived between the two water amounts added. However, at same water content, the polyester and high-performance polyester fabrics were perceived wetter than the cotton and polyester/blend fabrics. Although these differences were not statistically significant, the authors speculated around the reasons behind the differences. A first observation was made with regards to the fact that the fabrics were treated with the same absolute amount of water and had the same volume (cm^3). Nevertheless, despite this, fabric density was different and this was considered as potential cause for the reported differences in wetness perception. Additionally, another contributor could have been the magnitude of contact between the fabric and the skin. Plain and smooth structures, as the polyester and the high-performance polyester, could have had higher number of contact points with the skin, causing skin clinging when wet and evoking greater stickiness sensation, this associated to higher wetness perception (despite same water content).

In another study, Niederman & Rossi (2012) assessed thermal sensation, wetness perception and comfort of three different fabrics: polyester, cotton and blend (modacrylic, polypropylene, polyamide). The fabrics were wetted with 2 mL·240 cm^{-2} of water (0.008 mL·cm^{-2}) and afterwards, different amounts of water were allowed to evaporate to achieve, for each fabric, five different drying state: t0% (completely wet), t5%, t50%, t95% and t100% (completely dry). The time taken for each fabric to reach each drying state was calculated based on an infrared temperature-based method developed by the authors. The fabrics were then applied on the inner forearm of 12 participants. In both blend and polyester fabrics (both hydrophobic), no differences in thermal sensation (all rated as cold/wet) were observed between the first four drying states (t0%, t5%, t50%, t95%). In these fabrics, only the drying state t100% was perceived warmer/dryer. On the other hand, the cotton fabric showed an earlier step change in sensation, which was explained by the author in light of the slower drying and hygroscopic properties of the textile.

In the past, it was common to compare the effect of fabric hygroscopicity and hydrophilicity of natural and synthetic fibres (Yoo and Barker 2004; Liya Zhou et al. 2007; Qing Chen et al. 2010). However, nowadays more attention has been given to newly high-performance synthetic fabrics. These fabrics claim unique characteristics that distinguish them from conventional ones. In fact, these materials are non-hygroscopic but have good wicking properties. The latter should result in excellent moisture management properties, especially during heavy sweating, compared to conventional fabrics made from natural fibres. In this regard, Jeon et al. (2011a), investigated the difference threshold (the minimum amount of stimulus change required to produce a difference in the perception of wetness) of four experimental fabrics: cotton, polyester, high-performance polyester, polyester/polypropylene blend. It was found that, in simulated low sweat condition (standard stimulus 0.5 mL of water per 100 cm^{-2}, 0.005 mL·cm^{-2}). The cotton fabric presented the highest different threshold (0.27 ml of water per 100 cm^{-2}), whereas high-performance polyester had the lowest (0.19 ml of per 100 cm^{-2}). The authors reported that due to the initial faster absorption rate, in the cotton material water diffused through the specimen quickly and evenly, this potentially explaining why the participants hardly perceived the increment of water in this fabric. Conversely, the participants readily detected water content changes in the high-performance polyester material. According to the authors, due to the lower absorption rate, it is possible that the water added to the high-performance polyester did not readily diffuse through the fabric and it was held as free liquid at the surface; this likely causing the lower difference threshold. The provided explanations can be considered valid since in this experiment water was added to the inner side of the fabric with a pipette and, after this, the fabric was immediately applied to the skin. Therefore, using this approach, fabrics were not in steady-state of absorption. For high sweat conditions (1.5 mL of water per 100 cm^{-2}, 0.015 $mL·cm^{-2}$) the high-performance polyester showed the highest difference threshold (0.54 $mL·100\ cm^{-2}$) whereas the high-performance polyester/polypropylene blend showed the lowest (0.356 $mL·100\ cm^{-2}$), whereas the cotton was between the two (0.476 $mL·100\ cm^{-2}$). In line with this, the high-performance polyester fabric presented the fastest wicking rate (faster transport of water from one side to the other side of the fabric), which made difficult the perception of the water increment in the fabric. Based on these results, the authors concluded that, due to the fastest initial absorption and the highest different threshold, the cotton material would be more comfortable in the initial stage of sweating and/or in light sweat conditions. Conversely, at higher sweat level, the high performance polyester fabric, would feel drier than the other fabrics, due to the fastest wicking rate and largest different threshold in moisture perception.

Recently, Tang et al (2014a) conducted a skin regional study to characterise moisture absorption and transport properties of 20 types of woven fabrics, comprising different fibre composition, yarn type and fabric construction. The results from material testing were then compared with wetness sensation responses from human testing. Liquid moisture transfer was assessed by measuring absorption rate applying a gravimetric horizontal wicking test and the vertical wicking test according to AATC-79 Absorbency of Textile. Fabric absorbency was assessed with the GATS test. Moisture management properties were measured with the MMT, and absorption capacity was determined with a gravimetric sink test, according to Tang et al (2014a). To assess wetness perception of the fabrics, participants of both sexes were asked to slide and swipe their index forefinger around the pre-wetted portion of the sample. Wetness was scored using a 5 points scale, ranging from dry to very wet. The fabrics were wetted with the same absolute water amount of 0.1 mL. Fabric structure had a significant impact on wetness perception, with plain structures being perceived wetter than the others (2/2 twill, 1/5 twill, 2/2 rib, 4/4 rib). In this regard, the authors suggested that the plain structure has more intersection points along the yarn and higher yarn tortuosity (i.e. more ups and downs along the yarn), resulting in smaller inter-yarn voids for water absorption. Furthermore, a plain structure tends to be thinner with lower porosity among the five structures, which results in lower absorption capacity and less inter-yarn wicking. On the other hand, no significant effect of yarn on wetness perception was observed. Fabrics with an absorption time longer than 60 seconds (AATC-79 Absorbency of Textiles), presented the highest wetness perception. A strong liner positive relation was observed between the horizontal wicking area and wetness perception. This relation was mainly driven by fabric thickness, given that horizontal spreading area and wetness perception linearly increased with the increase in fabric thickness. The authors suggested that, due to the lower thickness, the larger horizontal wicking area allowed faster evaporation and skin cooling when in contact with the participants' finger. The higher skin cooling, in turn, affected wetness sensation. However, this can be true in an exercise condition, where sweat has enough time to evaporate and provide a skin cooling sensation. Conversely, in this study, the skin interacted with the wetted fabric only for 30 seconds and the fabrics were pre-wetted with water at room temperature, therefore, in this condition, it seems unlikely that liquid evaporation provided any perceivable cooling. Nevertheless, what seems more reasonable to point out is the fact that, due to differences in thickness, fabrics presented different volume, therefore different capacities to accommodate the added water. Given that the same absolute water content was added, the fabrics with lower thickness and volume presented higher relative water content and were more saturated than the thicker ones, the latter leading to differences in wetness sensation. A strong significant relation was observed between wetness perception and absorption capacity of fabrics. Although a strong predictive power was identified, the relation between wetness sensation and absorption capacity was not linear. Absorption capacity was expressed in $g \cdot m^{-2}$, and given the observed impact of fabric thickness (and volume) on wetness perception and horizontal wicking, perhaps a better prediction model could be obtained if absorption capacity is expressed as $g \cdot m^{-3}$. No relations were observed between wetness perception and the GATS test, the MMT results and vertical wicking measurements. The latter could have been due to incongruences between the experimental setups characterising the used material testing and the human testing.

1.5.12.4 Whole body studies

Human testing also includes experiments focusing on the impact that a whole garment has on a large body area, i.e. upper or lower body, as well as the whole body. These studies are here defined as whole body studies. These kinds of experiments usually adopt a more applied research approach. Whole body studies allow investigations of the combined effect of textiles and clothing factors on human responses in a wide range of climatic conditions. These investigations are typically performed under exercise conditions; therefore the impact of physical exercise and personal factors is also taken into account.

In a whole body experiment, Holmer (1985) compared the heat exchange and thermal insulation of two clothing ensembles, one made of wool, and the other of nylon. Participants wore the two ensembles during exercise for 60 min, followed by 60 min of recovery. It was found that the wool garment absorbed more sweat than the nylon garment (245 g versus 198 g). However, it was unclear whether the higher amount of sweat absorbed by the wool garment was due to the hygroscopicity of the fibre itself or to other fabric factors, such as thickness and volume. In fact, it is likely that the wool garment may have had a slightly higher thickness that the nylon fabric, therefore higher volume to collect more moisture. In support, Bakkevig and Nielsen (1994) found that a wool underwear absorbed more sweat (39 g) than a polypropylene underwear (10g); however, the wool garment was 1.95 mm thick and the polypropylene 1.41 mm, suggesting fabric thickness as contributing factor. The main outcome of these studies was the role of fabric hygroscopicity as a major factor in reducing moisture build-up in the microclimate during the transient state (Hong et al., 1992; Yasuda et al., 1994). Nevertheless, it was not investigated whether the reduced wetness and humidity, due to fabric hygroscopicity, corresponded to changes in physiological and/or perceptual human responses, i.e. sweating and sensation of wetness, respectively.

Later on many researchers investigated the impact of clothing fibre type on physiological responses, such as body core and skin temperature as well as clothing microclimate (Behmann 1971; Holmer and Elnas 1981; Li et al. 1992a; Li 2005). Early work with synthetic clothing has either shown no difference or an increased core temperature when wearing clothes made of synthetic fibres compared with cotton fibres (Ha et al. 1995b; Ha et al. 1999). Other studies observed no differences in thermoregulatory responses between different fibre contents and fabric construction (Gavin et al. 2001; Laing et al. 2008; Sperlich et al. 2013). On the other hand, several recent studies have shown a significant reduction in skin temperature with either a blend of synthetics (Roberts et al. 2007) or natural fibres (i.e., cotton and soybean) compared with cotton fibres (Dai et al. 2008). Controversial results between studies can be due to differences in the research methodology applied. The available studies adopt different environmental conditions, exercise protocol as well as participants' sexes and fitness levels. The latter, besides leading to controversial results between studies, also makes unreasonable the comparison of results between different investigations. In this regard, Table 1 reports a number of experiments that have studied differences between garments made of synthetic and cotton materials (Ha et al. 1995a; Ha et al. 1995b; Ha et al. 1996; Kwon et al. 1998; Gavin et al. 2001; Youngmin Jun et al. 2009; Brazaitis et al. 2010; De Sousa et al. 2014). From the table, large differences in the research methodology and conditions adopted can be observed.

Table 1 Selection of the research methodologies adopted by studies comparing natural and synthetic garments in whole body experiments.

Authors	Participants (n)	Fitness level	Exercise mode	Ergometer	Exercise protocol	Exercise Intensity	Temperature (°C)	Relative Humidity (%)	Wind speed ($m \cdot s^{-1}$)
Ha et al. (1995a)	6 F	NS	100 min passive	NA	NA	NA	27 - 37	60	0.1
Ha et al. (1995b)	5 F	NS	intermittent	cycle	(10 min exerc+ 10 min rest) x 4	30% VO_{2max}, 50 rpm	24	50	0.14
Ha et al. (1996)	7 F	NS	intermittent walking	treadmill	30 min + 60 rec	6 $km \cdot h^{-1}$	24	65	0.14
Know et al. (1998)	7 F	NS	intermittent	cycle	(10 min exerc+ 5 min rest) x 6	NS	30	50	0.14 & 1.5
Gavin et al. (2001)	8 M	Trained (67 $mL \cdot kg^{-1} \cdot min^{-1}$)	intermittent	treadmill	30 min running at 70% + 15 walking at 40% + 15 min rest	NS	30	35	0.9
Youngmin et al. (2009)	6 M	NS	NS	stepping	(20 min + 20 min rest)	NS	30	50	NO WIND
Brazaitis et al.(2010)	8 M	recreationally active	intermittent	treadmill	(20 exerc+5 rest) x3 + 60 min rest	8 $km \cdot h^{-1}$, 1 % grade	25	60	0.3
De Sousa et al. (2014)	10 M	recreationally active	continuous	cycle	45 min	50 % VO_{2max}	30	60	NO WIND

Another aspect to consider when conducting whole body studies is the selection of the experimental garments. In this regard, there are two scenarios to take into account. First of all, if the purpose is to assess and compare garment functionality and to select the best performing one, from both physiological and perceptual viewpoints, matching fabrics for parameters which should be controlled is not relevant. On the other hand, if the aim of the study is to investigate the role of a specific property, e.g. fabric fibre content, it is of critical importance to match the garments for factors which might show misleading results, e.g. air permeability, thickness, garment fit. In this regard, a recent whole body study investigated the impact of fabric construction and fibre type on thermoregulatory and sensorial responses as well as clothing microclimate (Davis et al. 2017). The study compared three garments presenting different fibre contents such as 100% cotton, 50% cotton/50% soybean and 100% polyester. Eight male participants were recruited for the study which consisted of three running trials at 60% of the VO_{2max} (~11 $Km \cdot h^{-1}$), at 32 °C and 35% relative humidity. In addition to differences in fibre content, the garments presented different fabric density and weight. Furthermore, the polyester material was claimed to facilitate ventilation, nevertheless air permeability values were not provided. No differences were found in physiological responses of core and skin temperature and heart rate between the three garments. Perceptual responses of skin wetness and thermal sensation were not different between the garments. The only parameter which was found to be affected was microclimate temperature at the chest, which was significantly different (~1 °C) in the polyester compared to the cotton garment, but it was not different compared to the blend fabric. Nevertheless, the lower microclimate temperature did not correspond to lower temperature sensation. The lower microclimate temperature was used by the authors to show that fibre type has an impact on microclimate temperature, this potentially leading to an improved sport performance. However given that unmatched fabrics were used, it is not straightforward to conclude whether the difference in local microclimate was caused by the fibre type per se, or by structure, weight or even by the claimed higher ventilation in the polyester garment. Additionally, since the lower microclimate temperature at the chest did not impact skin temperature or thermal sensation, it seems unreasonable to hypothesise a potential impact on exercise performance, which was speculated by the authors.

In whole-body experiments, a number of researchers have also looked at the sensorial responses occurring while wearing clothing, such as thermal, wetness and stickiness sensation as well as comfort. Wong and Li (2004) examined the relationship between human physiological (skin temperature and humidity) and sensorial (thermal and moisture sensations) responses in male and female participants wearing a tightly fitting garment during exercise. Participants were required to run on the treadmill for 20 min in an environmental chamber maintained at 29 °C and 65% relative humidity. Skin temperature was measured at the chest, abdomen, inner thigh, outer thigh, upper back and lower back. Participants were asked to report local thermal sensation and wetness perception as well as overall clothing comfort, for the same body areas. A strong linear relationship (average r^2 = 0.96) was found between humidity and moisture sensation at all the studied body areas, however, the linear relationship between temperature and thermal sensation was relatively weaker (average r^2 = 0.71). Clothing comfort was best described by thermal sensation at the outer thigh and humidity at the inner thigh (r^2 =0.76). This suggested that clothing comfort can be predicted on the basis of human physiological and psychological responses in relation to temperature/thermal sensation and humidity/moisture perception.

Later on Li (2005), in a whole body trial, assessed thermal and moisture sensation of wet jumpers made of wool and acrylic. The fabrics presented same weight, thickness and structure and were both made hydrophobic using a chemical treatment. The experiment was conducted in an environmental chamber maintained at 20 °C and 80% relative humidity. The wetness of the garments was achieved by simulating rain in the chamber. Twelve male participants performed 20 min of walking exercise on the treadmill. The presence of rain considerably decreased warmth sensation which started to recover as soon as the rain stopped. Interestingly, the drop in perception of warmth was greater in the acrylic compared to the wool jumper. Similarly, the perception of moisture increased very quickly during rain and continued to rise slowly after the rain has stopped. The dampness sensation was stronger when wearing acrylic compared to the wool jumper. The study demonstrated that hygroscopic fibres can reduce and delay the resulting thermal and moisture discomfort sensations induced by humidity rise and temperature drop at the clothing outer surface.

1.5.12.5 Considerations

In skin regional studies, the effect of garment design, garment fit and seams is not considered. The pumping effect resulting from the body and air movement is neglected. Finally, the impact of the air gap and contact area between the body and the garment is not considered. Nevertheless, results from skin regional studies can provide fundamental knowledge regarding the principles governing heat and mass transfer in clothing and their impact on human sensorial responses. On the other hand, in whole body studies, it is difficult to isolate the effect of textile parameters from the effect of clothing and personal factors. Nevertheless, results from whole body studies can have an immediate impact on real use conditions.

Overall, while the mechanisms underpinning wetness perception at skin level have been largely investigated, fewer studies have examined how textile and clothing factors modulate cutaneous sensations arising from the presence of wetness and humidity. Furthermore, due to the significant impact of tactile cues on wetness perception, skin regional studies should also examine dynamic fabric-to-skin contact conditions. Additionally, most of the available skin regional studies have investigated skin wetness perception using pre-wetted fabrics as stimuli. When fabrics are pre-wetted with water at room temperature, skin cooling sensations mainly occur from the increased thermal conductivity of the fabric in contact with the skin. Nevertheless, not many studies have investigated skin wetness perception in exercise conditions, where skin cooling sensations arising from sweat evaporation can also play a role. With regard to transient conditions, moisture in fabrics is a critical factor affecting comfort, in particular after exercise, when the reduction in metabolic heat production and the higher thermal conductivity of wet clothing can cause post-exercise chill drop. In light of this, moisture sensation in textile materials should be investigated during physical activity as well as during active and/or passive recovery periods. Finally, although the critical impact of skin and clothing wetness on human comfort, performance and health has been well established, the spatial and temporal development of clothing wetness (sweat-induced) has not been investigated. Specifically, it is unknown how much of the sweat produced during exercise is absorbed by the garment, how this distributes across different garment zones and what level of moisture saturation is reached.

1.6 Summary of the literature review

From this literature review it was concluded that:

- The environment-human-clothing system is a complex organisation characterised by the interaction of its various factors. The interaction of these numerous factors causes the initiation of human thermal responses and impacts the way in which clothing performs.

- Clothing is an essential source of protection for the human body, however providing a physical barrier between the skin and the environment it can impair body heat loss, affecting body thermal balance and causing thermal as well as sensorial discomfort.

- The presence of wetness at the skin-clothing interface represents one of the highest sources of discomfort and, in extreme conditions, can also have serious implications in terms of health and survival.

- A number of studies have been conducted to understand the complex sensory modalities underlying wetness perception at skin level. With regards to clothing, extensive research has been undertaken to study the textile parameters involved in the process of moisture transfer and absorption. Nevertheless, the link between fabric properties and human responses related to fabric wetness is poorly understood.

- Material test methods, conducted with specific apparatus, are commonly applied to evaluate objective improvements in fabric heat and mass transfer properties. However, the impact of textile innovations on human thermophysiological and sensorial responses is unclear and sometimes inconclusive.

- Maps of sweat rate patterns across the human body have been made available. However, crucial information regarding the amount of secreted body sweat that is absorbed and retained by the worn garments and on how this distributes across different garment regions is still unknown.

- A close cooperation is needed between physiologists, sport scientists, textile engeneers and clothing designers in order to translate human physiological and sensorial outcomes into garments with efficient thermal and moisture features.

1.7 Research aims

Based on the limitations outlined in this literature review, the aims of this thesis will be:

1. To identify and examine the textile parameters that modulate cutaneous sensations and perceptions related to skin and clothing wetness as well as related sensations of discomfort.
2. To characterise sweat absorption, distribution and the corresponding moisture saturation percentage in an upper body garment, in conditions of exercise-induced sweat production.
3. To develop a comprehensive research methodology to study the impact that textile moisture parameters have on human responses (sensorial and physiological), individually as well as in combination with clothing factors.

1.8 Rationale

The goal of the sportswear company adidas is to maximise athletes sport performance and provide the consumers with the best imaginable apparel product. This can be achieved by improving clothing functionality through its impact on the main aspects of wear comfort and human performance. As such, this thesis proposes a human-based paradigm as rationale for clothing evaluation and development.

CHAPTER 2

Experimental methodology

2.1 Introduction

This chapter provides an overview of the methodology developed and applied to answer the research questions highlighted in Chapter 1 and throughout this PhD. The current research is articulated in two stages. In the first research stage, the impact of textile properties on human sensorial and perceptual responses was investigated adopting a mechanistic approach (Study 1 and Study 2). In fact, the impact of specific textile parameters on human responses was isolated from the effect of clothing factors, such as fit and design, as well as personal factors and exercise.

Before moving to the second research stage, In Study 3 we addressed potential biases (anchoring biases) that could occur when sensorial scores are repeatedly reported by participants in transient exercise conditions. This study allowed recognition and mitigation of the bias, which was relevant for the interpretation of future perceptual scores obtained in transient exercise conditions, and to improve scientific rigour. The data collection of this study was conducted in the adidas headquarter, adidas FUTURE Sport Science Team, in Herzogenaurach, Germany.

In the second research stage, a more applied approach was adopted in order to investigate the combined impact of personal, textile and clothing factors on human responses in conditions of exercise-induced sweat production (Study 4 and Study 5). In these studies, a warm environmental condition (27 ºC, 50% Rh) was targeted and a single layer clothing ensemble was used, including a short-sleeved upper garment, shorts, and short socks. The investigations mainly focused on human outcomes resulting from the interactions with the upper garment, as well as the upper garment performance.

Study 6 consisted of a methodological investigation, mainly involving regression analyses between garment regional sweat absorption ($g{\cdot}m^{-2}$) and temperature (ºC). We hypothesised that garment regions with greater sweat content will result in higher temperature drop from environmental temperature. Based on this principle, the end goal was to assess whether infrared thermography could be used as an indirect method to estimate garment regional moisture content, in a non-destructive and cost-effective way, as compared to the gravimetric method applied in Study 5.

2.2 Ethical Clearance

The laboratory studies reported in this thesis were all approved by Loughborough University Ethics Committee. The procedure to obtain Ethical approval involved the completion of a Risk assessment, experimental protocols and study's written information sheet. For all the experimental studies the following generic experimental protocols were adopted:

- G10/P10: Regional sensitivity to a cold and warm stimulus over the body surface.
- G03/P13: Thermoregulatory effect of warming in air.

Following reading the information sheet that described the purpose of the study, all participants gave written informed consent for participation in the study and completed a health screening questionnaire (Appendix A, B and C). All studies were conducted in accordance with the World Medical Associations Declaration of Helsinki for medical research using human participants (WMA, 2008).

2.4 Participants recruitment

For all the experimental studies, participants of Western European origin were recruited and the age range was set between 18-33 years. This was to reduce any systematic error due to ethnicity and age-related differences in thermoregulatory responses, skin properties, and thermal as well as tactile sensitivity. Other inclusion criteria for participation were:

- No history of neuromuscular and cardiovascular disease and sensory-related disorders.
- No history of muscle-skeletal injury in the previous 12 months to the study.

For Study 1 and Study 2, participants of both sexes were recruited from the Loughborough University student cohort. In these two experiments participants did not perform any physical exercise, however, since the studies involved the use of functional fabrics, recreationally active (at least 4-6 hours per week) participants were recruited.

For Study 3 and Study 4, young male recreationally active participants (strength and conditioning as well as aerobic exercises at least 4 times per week) were recruited from the participants' database used at adidas FUTURE Sport Science Team (Study 3) and from the Loughborough University student cohort (Study 4).

For Study 5, long distance male runners, with a maximum oxygen uptake (VO_{2max}) > 55 $mL \cdot kg^{-1} \cdot min^{-1}$ were recruited from the Loughborough University student cohort.

2.5 Regional skin studies

Study 1 and Study 2 were performed in a thermoneutral environment maintained at ~25 °C, relative humidity ~50% and air velocity < 0.05 m/s. In these two studies, the experimental fabrics used were pre-wetted by the investigator and applied to a single pre-defined body area (upper back in Study 1 and inner forearm in Study 2). With regards to the wetting procedure developed, approximately 2 hours before the experiment, each fabric was positioned onto a plastic film and water was added by using a micropipette (SciQuip LTD, Newtown, UK) (Fig 1). When the water was in equilibrium with the fabric, each fabric was placed into a plastic bag which was securely sealed to prevent water evaporation. A detailed description of this procedure is in the 'Method' section of Study 1 (Chapter 3) and Study 2 (Chapter 4).

Figure 1 Fabric wetting procedure.

2.6 Whole-body, exercise studies

Three experimental studies were performed under exercise-induced sweat production conditions (Study 3, Study 4 and Study 5). Short sleeved upper garments, presenting a same regular fit were used in the whole body studies (Fig 2). However, the garments differed in fibre composition, thickness, air permeability and knit structure across the three studies. Material specifications of the garments are reported in the 'Method' section of Study 3 (Chapter 5), Study 4 (Chapter 6) and Study 5 (Chapter 7).

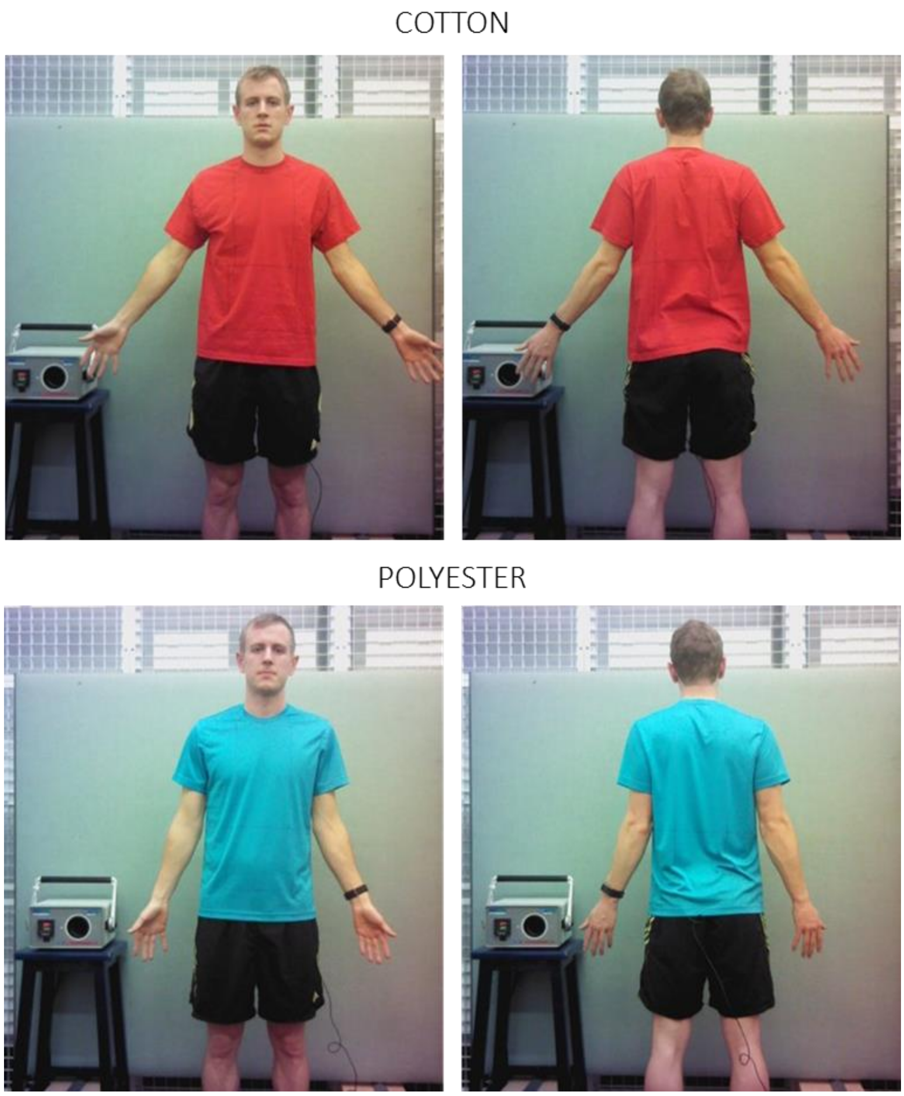

Figure 2 Front and back picture of the experimental garments used in Study 5.

The type of activity selected was running exercise and the intensity, as well as duration, varied across the three studies. In both Study 3 and Study 4, participants were asked to self-select, in a pre-test, a fixed speed they could run comfortably for 1 hour. In study 3 the duration was of 50 minutes in total, whereas in Study 4 participants run for a total of 30 min. In Study 4, a shorter running duration was selected for reasons related to the applicability of the results as well as for safety reasons. Specifically, a duration of 30 minutes was selected to simulate the type of running activity typically performed in an indoor environment e.g. at the gym. Another reason contributing to the selection of a shorter exercise duration was linked to the applied air flow which, for methodological reasons (described in Study 4), was set to negligible levels (0.2 $m \cdot s^{-1}$). In fact, in absence of substantial air flow, pilot testing showed a fast rise in T_{core} to values set as 'unsafe' in the Ethical clearance (absolute values above 39 ^{o}C). As such, shorter exercise duration was preferred.

In Study 5 participants ran for 50 min at the same individually fixed speed, corresponding to 70% of VO_{2max} (maximum oxygen uptake). This exercise intensity was selected to obtain results which could be related to previous studies (Smith and Havenith 2011; Smith and Havenith 2012). The experiments in study 5 were conducted in a small wind tunnel (1.5 $m \cdot s^{-1}$ wind speed) located in a climate-controlled chamber maintained at 27 ^{o}C and 50% relative humidity (Fig 3).

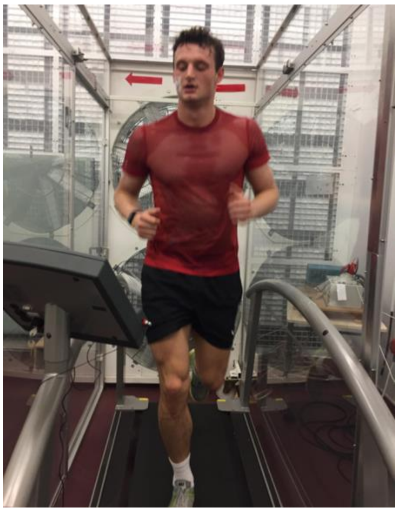

Figure 3 Participant running on the treadmill located into the wind tunnel which was placed in the environmental chamber.

2.6.2 Garment local sweat absorption

In Study 5, analyses of T-Shirt local sweat absorption (ABS_{local}) were conducted in 22 T-Shirt regions, 12 for the front and 10 for the back. The relevant sweat absorption T-Shirt zones were selected based on temperature patterns highlighted in infrared pictures (conducted in pilot testing), obtained once the T-shirt was taken off the body. At the end of each run duration, analyses of local sweat absorption were conducted by cutting up the pre-marked T-Shirt regions and weighing the individual sections before and after drying. Details regarding the determination of garment regions and local sweat absorption measurements are reported in the 'Method' section of Study 5 (Chapter 7).

2.6.2 Infrared imaging procedure

The upper garments presented 21 regions of interest (ROI) in total. A procedure similar to that developed by Fournet (2013) was adopted to obtained quantitative temperature data of the ROI and to provide average thermal patterns (temperature distribution across the garment), visually accessible with a colour scale.

2.6.2.1 Infrared thermal camera

A FLIR T620 (FLIR Systems Inc. Wilsonville, USA) infrared camera was used. Specifications are reported in Study 6, Chapter 8.

2.6.2.2 Image acquisition

A standardised procedure was developed for the acquisition of the infrared images. The procedure is described in Study 6 (Chapter 8). For the image acquisition, the garment was fitted to a custom-made T-Shirt-like shape stand (Fig 4). The stand was made of wood and treated with hydrophobic finish to prevent water transfer from the T-shirt to the stand.

Figure 4 Custom-made T-Shirt-like shape stand, used for the image acquisition of the experimental garment in Study 5.

2.6.2.3 Image pre-processing

The following five parameters were required for the image pre-processing:

- Object emissivity (ε)
- Relative humidity (rh)
- Ambient temperature (T_a)
- Object distance (D_{obj})
- Reflected ambient temperature (T_{refl})

Fixed values were used for object emissivity (ε = 0.98) and object distance was consistently kept at 2 m perpendicular from the camera. Relative humidity and T_a were adjusted in the camera's settings, according to the value recorded in the climatic chamber. Image pre-processing was performed using the software FLIR Tools (version 2.0.11333.1001, 2001, ©FLIR Systems), where the different parameters are implemented for each thermogram. The software was also used to estimate reflected ambient temperature (T_{refl}) on the thermogram. Using the software FLIR ThermaCam Researcher Pro 2.8 (FLIR Systems Ltd., West Malling, Kent, UK), the fully adjusted thermogram was saved as Matlab file (.mat) for the image processing.

2.6.2.4 Image processing

The development of the image processing procedure was performed using the software MATLAB 7.8.0 (MATLAB R2013a, The MathWorks Inc., Natick, USA). Matlab scripts modified from those developed by Fournet (2013) were used for the analysis. The steps involved in the image processing are reported below.

Before processing the images, the matrix values of each thermogram were corrected from Kelvin into degrees Celsius. At this point, the imaging processing was initiated. The first process, called *image registration,* involved the selection of control points (CP) on a reference image. A manual selection of CP was conducted digitally on the pre-processed thermogram, with standard landmarks around the T-Shirt contour. The locations of all the different T-Shirt landmarks are presented in Figure 5. The *cpselect* function, in the MATLAB image analysis toolbox, allowed the selection of CP on individual thermograms next to the reference thermogram (Fig 5). In addition to the manually select CP, additional landmarks were computed using spatial geometry (coordinates of the intersections between straight lines joining 2 CP) in order to define the 22 ROI and allow segmentation of the T-Shirt (Fig 6). Regional temperature data were then automatically computed (*regionprops function*) from each of the 21 ROI, i.e. average temperature, median temperature, minimal temperature, maximal temperature and standard deviation.

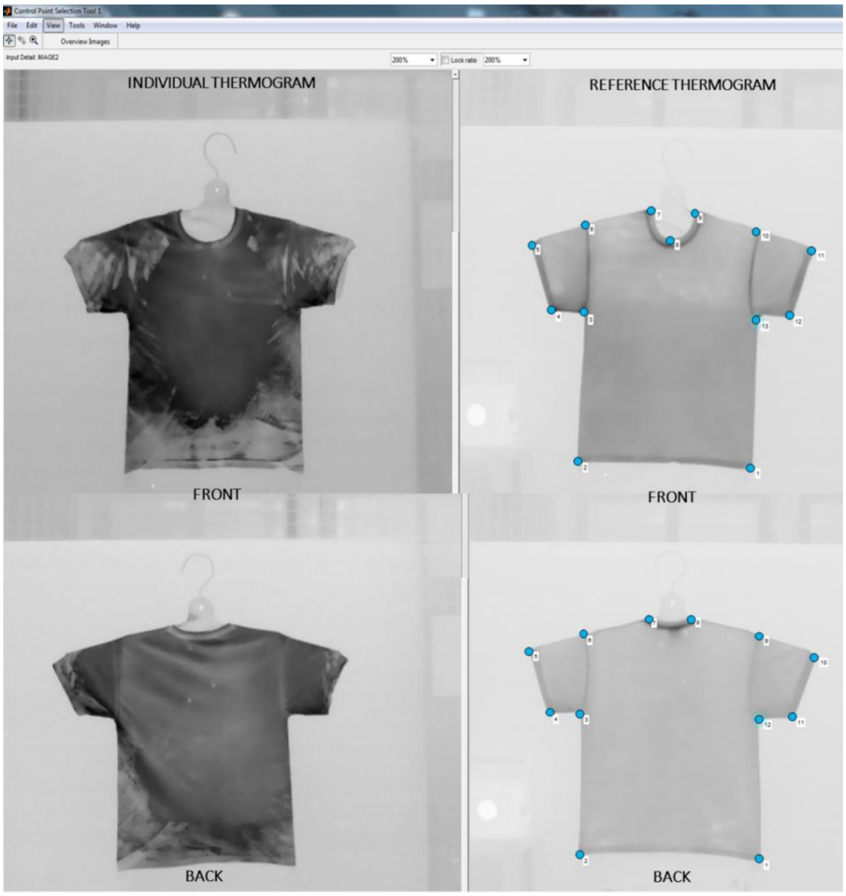

Figure 5 Image registration performed in Matlab. The process involves the manual selection of control points (CP) on the individual thermogram (*left*), according to the pre-selected CP (blue dots) on the reference thermogram (*right*).

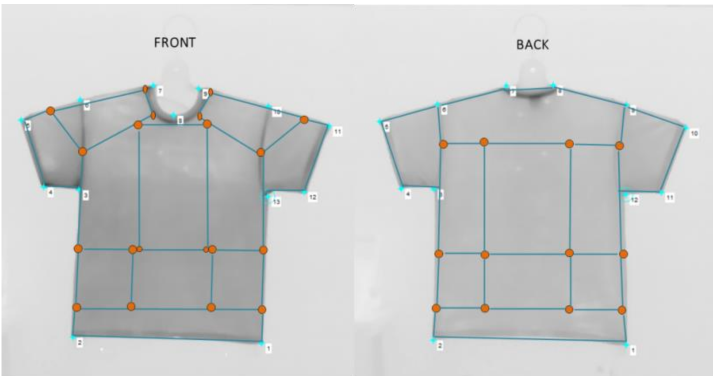

Figure 6 Segmentation of each thermogram into the 22 region of interest (ROI). The ROI were identified in each individual thermogram using, in addition to the t control points (CP, blue dots) additional landmarks (orange dots).

The second phase of the image processing procedure was the *image transformation* (translation and morphing). To account for differences in T-Shirt size and position (although it was standardised as much as possible using the T-Shirt stand), all thermograms were morphed (i.e. adapted) onto the reference T-Shirt shape. Morphing was performed based on the CP coordinates of the input thermogram and the reference thermogram via a landmark-based algorithm operating a 2^{rd} order polynomial transformation. The algorithm was launched from the *cp2tform* and *imtransform* function embedded in the MATLAB image analysis toolbox. The morphing process was repeated for each thermogram separately after selection of CP so that the temperature spatial information was translated into the standard T-Shirt shape. The individual morphed thermograms were then averaged to obtain a final T-Shirt map for each time point of temperature distribution. Figure 7 summarises the different stages of the image processing procedure.

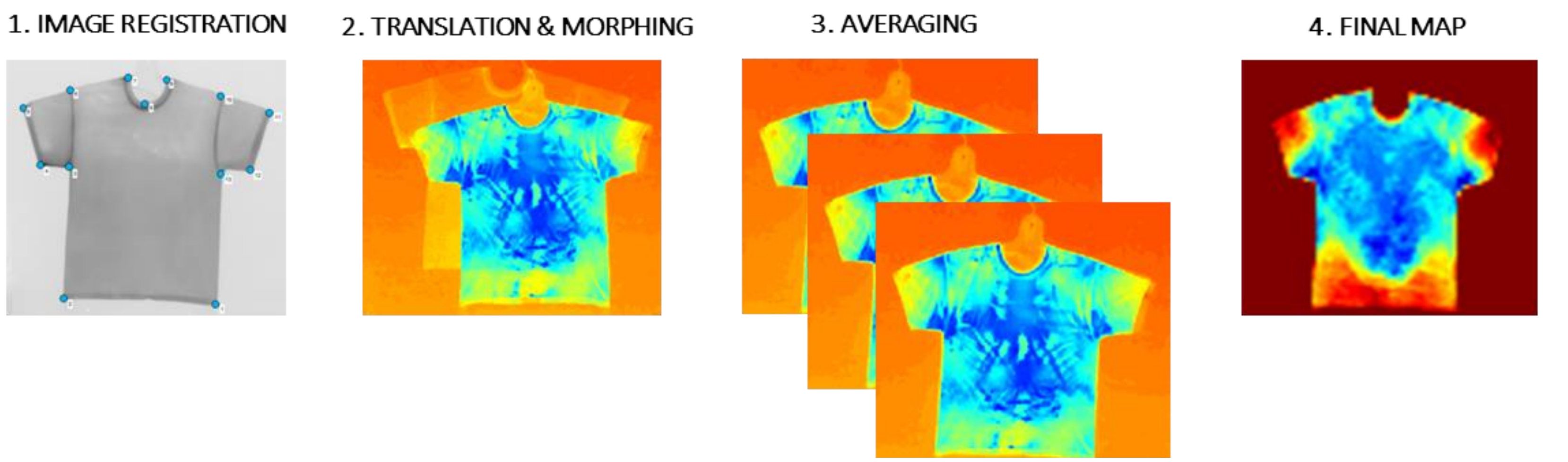

Figure 7 Image processing sequence using MATLAB. Image registration involves the manual selection of CP (control points). Each individual thermogram is then morphed and translated to the reference thermogram. The individual thermograms are then averaged for for the creation of a final T-Shirt map of temperature distribution.

2.7 Body temperature measurements

In Study 1 and Study 2 local skin temperature during the contact with each fabric was measured with two fine wire (0.025 mm diameter, time constant of 0.003 sec.) type T thermocouples (RS Components, Northants, UK). The thermocouple temperatures were monitored and recorded every second throughout the application of the stimulus via a Grant Squirrel SQ2010 data logger (Grant Instrument Ltd., Cambridge, UK).

Local skin temperature was calculated from the mean of the two measured spots. Local skin temperature drop (Local T_{sk} Drop), resulting from the application of each wet fabric sample on the skin, was calculated according to:

Local T_{sk} Drop = PRE Local T_{sk} – POST Local T_{sk}

Where:

> *PRE Local T_{sk}* is the local skin temperature before the application of the wet fabric (baseline) in °C.
>
> *POST Local T_{sk}* is the resultant local skin temperature recorded at second 15 during the application period in °C.

In Study 3 skin temperature of 5 body sites (check, abdomen, upper arm, lower back and back lower thigh) was measured throughout the experimental trial, with iButtons wireless temperature loggers (Maxim, San Jose, USA). From these five body sites, mean skin temperature, sampled every minute, was estimated according to the work of Houdas and Ring (1982):

$$\begin{aligned} Mean\ T_{skin} &= (cheek * 0.07) + (abdomen * 0.175) + (upper\ arm * 0.19) \\ &\quad + (lower\ back * 0.175) + (back\ lower\ thigh * 0.39) \end{aligned}$$

In Study 4 and Study 5 rectal temperature was measured to monitor changes in body core temperature. Participants were asked to self-insert a rectal probe (Grant Instrument Ltd, Cambridge, UK) 10 cm beyond the anal sphincter. Rectal temperature was recorded via a portable data logger (Grant Instrument Ltd, Cambridge, UK) connected to the thermistor's probe.

Before testing, the thermocouples, iButtons and rectal probe were calibrated by placing the measuring junction of each thermocouple in a circulating water bath whose temperature was monitored with a certified mercury thermometer.

2.8 Perceptual responses

The direct study of human sensations and perceptions in relation to clothing involved the use of psychophysical scales. The guidelines provided by the International Standard, Ergonomics of the thermal environment - Assessment of the influence of the thermal environment using subjective judgement scales (ISO 10551:1995) were followed to construct the scales used to measure human sensorial parameters. Psychophysical scales have been widely used in clothing science (Hollies et al. 1979; Plante et al. 1995; Schneider et al. 1996; Kaplan and Okur 2009; Jeon et al. 2011; Niedermann and Rossi 2012; Tang et al. 2014). Generally, visual analogue scales (VAS) are considered preferable when high level of resolution in the measurement of a particular sensation is needed. However, pilot testing for this PhD research highlighted that the use of VAS made the scoring process difficult for the participants when a large number of stimuli is scored. This was mainly due to lack of numbers and/or descriptors between the two anchor points at the extremes of the VAS (example in Fig 8A). In fact, the qualitative attributes between the anchor points, could be used as references by the participants during the scoring process. On the contrary, Likert scales have the benefit of presenting descriptors, although these types of scales are usually characterised by no more than 9 descriptors (example in Fig 8B), resulting in a significantly lower resolution compared to the VAS.

In the first research stage (Study 1 and Study 2) of this PhD, a large number of fabrics were examined and in the second research stage, sensorial scores of garments were repeatedly reported, at set intervals over time, therefore in both research approaches a high level of resolution was required. As such, based on this evidence and extensive pilot testing for this PhD research a new type of psychophysical scale was developed. The new scale can be defined as a hybrid scale since it presents features of both VAS and Likert scales. Similar to a VAS, the scale has a large resolution, however, rather than having only two descriptors, at the anchor points, it presents intermediate numbers and some descriptors linked to the numbers (Fig 9A, 9B), this being a characteristic of Likert scales. The criteria for the development of the scale's resolution and descriptors were applied based on results from pilot testing. For instance, each descriptor was divided into different points to allow a gradual change from one to another descriptor and also to give to the participants the option to discriminate between small changes within the same descriptor. Using this type of ordinal scale, participants are asked to verbally self-report the score of a specific attribute or sensation, e.g. wetness, along the numerical value continuum. This type of scale was used to develop the scales used to measure wetness perception, thermal sensation, thermal comfort, stickiness sensation, texture sensation, pleasantness sensation and wear discomfort scale, measured in this PhD research (Fig 9A, 9B). The same wetness perception scale was used for all the experimental studies reported in this thesis. The same stickiness sensation scale was used in Study 2, Study 3 and Study 4. The same texture sensation scale was used in Study 2 and Study 4. Pleasantness scale was used only in Study 2. The dis(comfort) scale was used in Study 1 to measure thermal comfort and in Study 3 and Study 4 to measure wear dis(comfort). Two modified versions of thermal sensation scale were used in Study 3 (Fig 10A) and Study 4 (Fig 10B), respectively. The scale was modified in both studies to increase the resolution on the positive side of the scale, linked to 'warmth' descriptors.

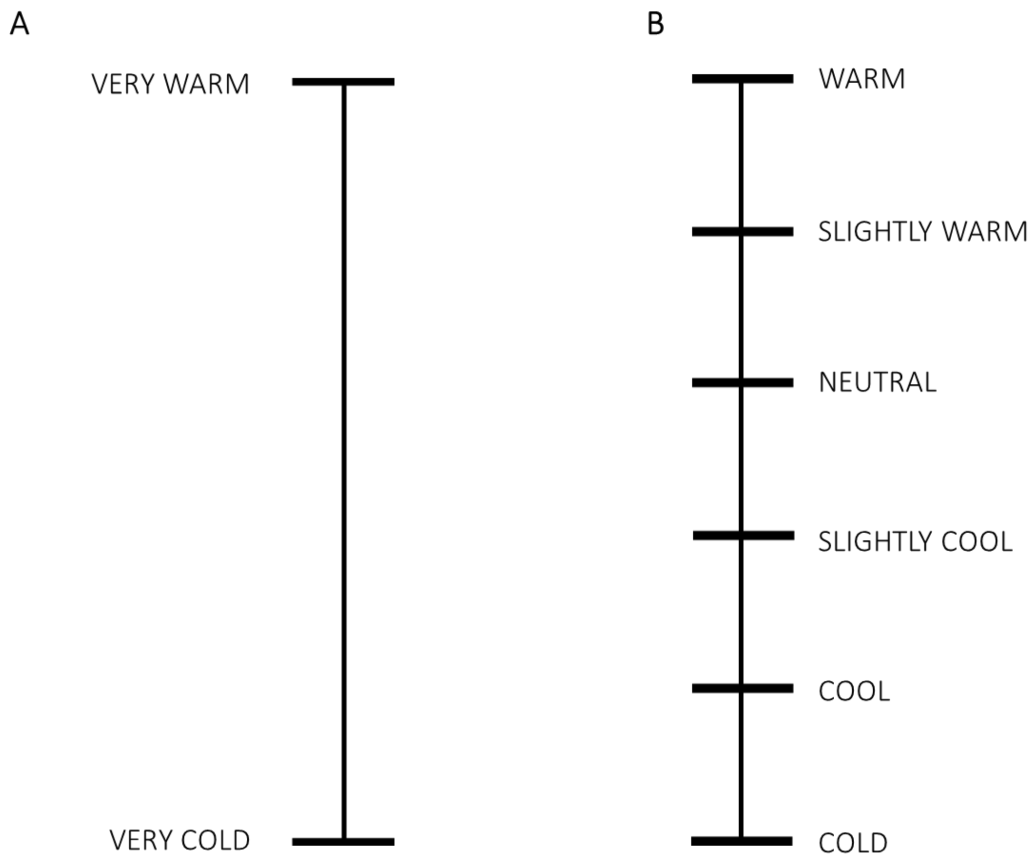

Figure 8 Example of a VAS (visual analogue scale) (A) and of a Likert scale (B).

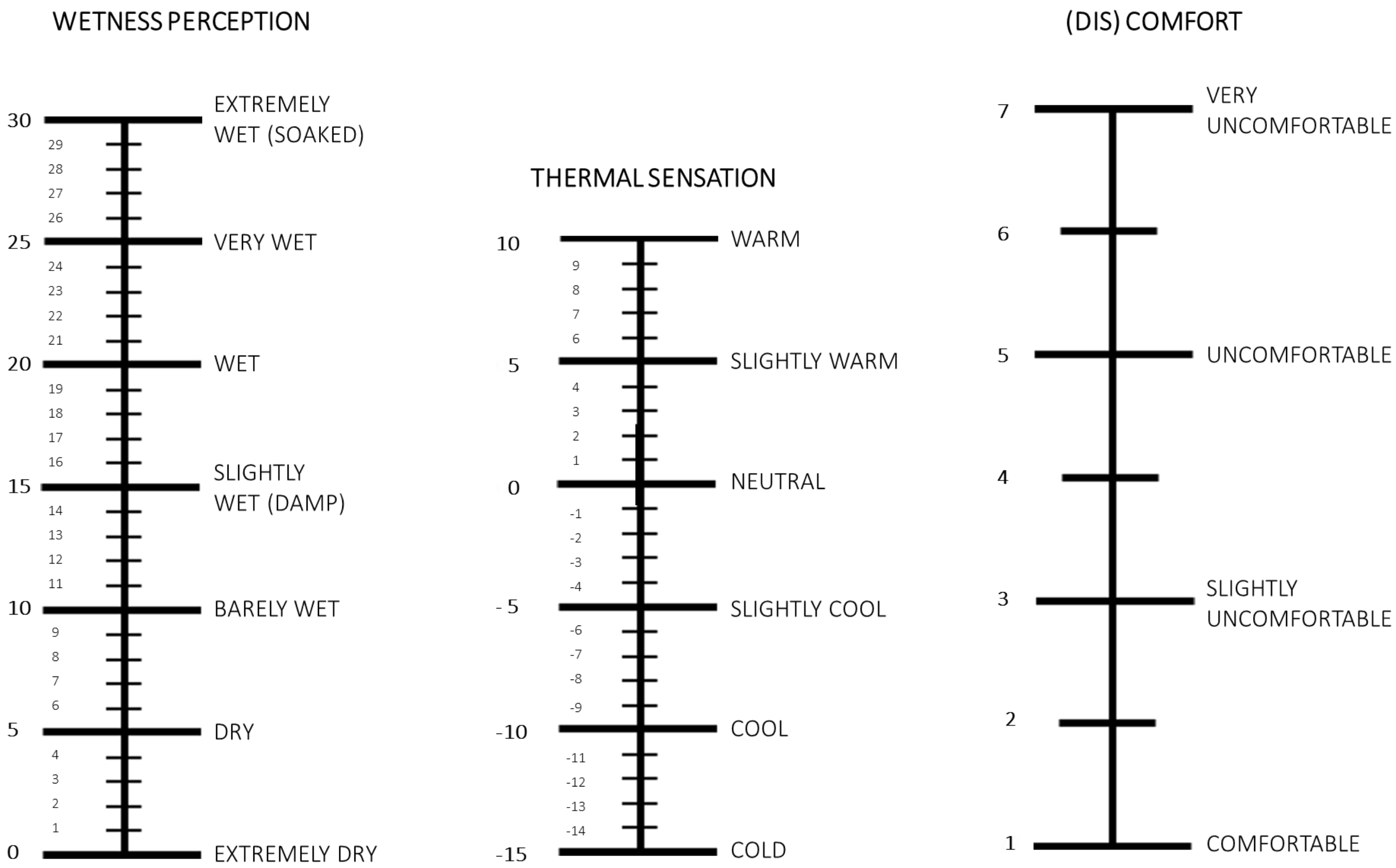

Figure 9A Wetness perception, thermal sensation and dis(comfort) scales, developed using the new developed type of psychological scale.

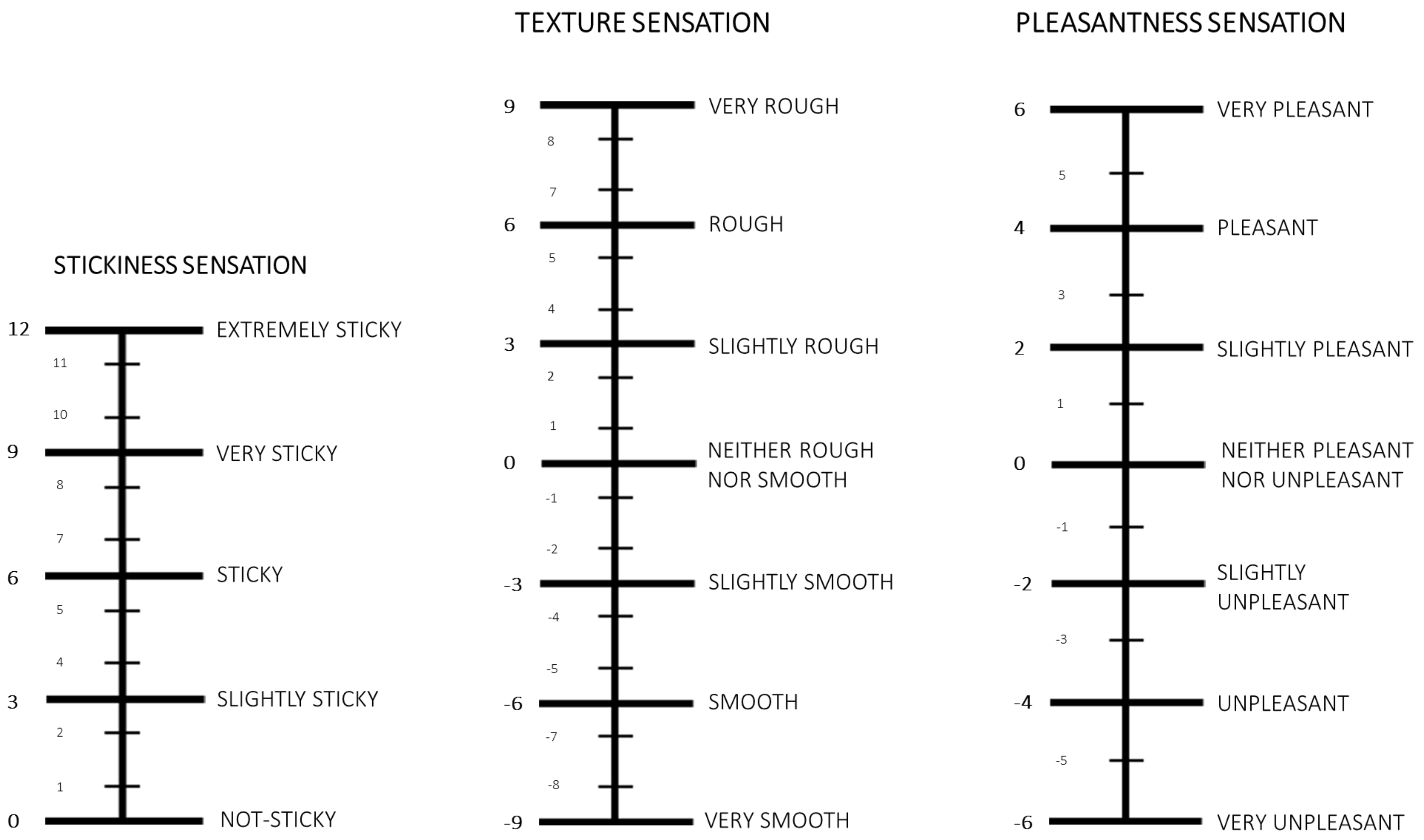

Figure 9B Stickiness sensation, texture sensation and pleasantness sensation scales, developed using the new developed type of psychological scale.

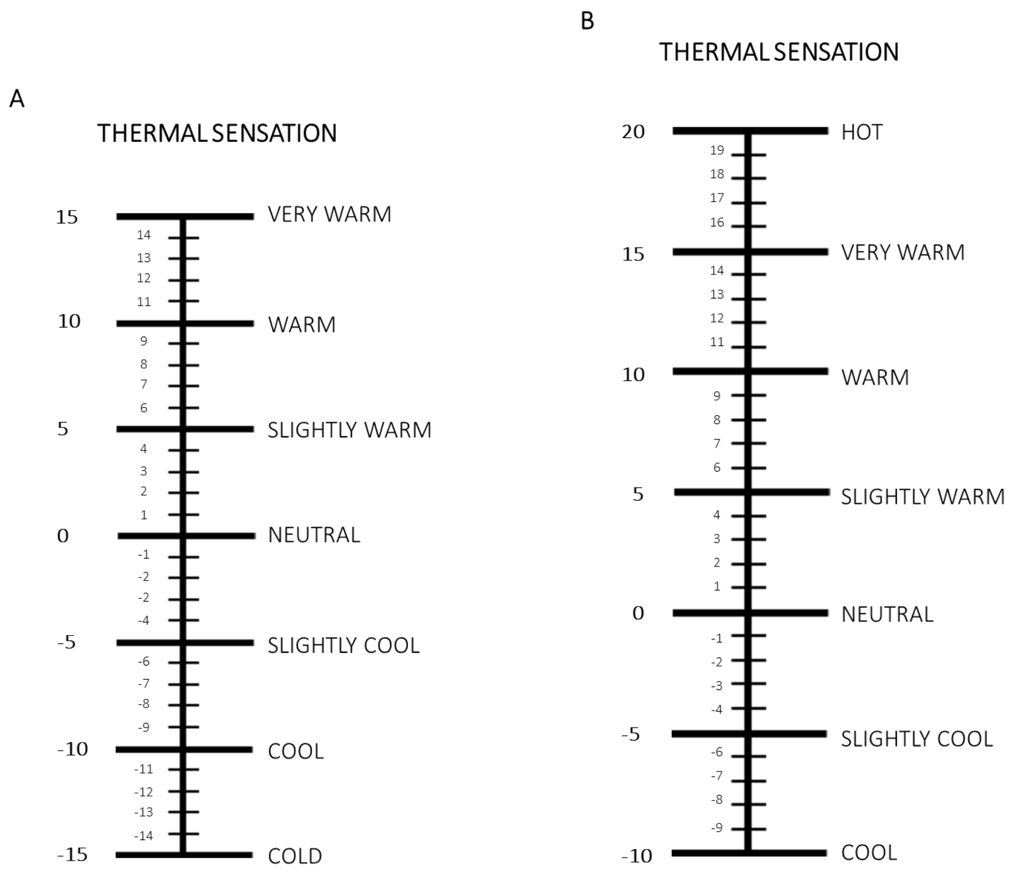

Figure 10 Modified thermal sensation scales used in Study 3 (A) and Study 4 (B).

CHAPTER 3

Laboratory study 1

Human wetness perception in relation to textile water absorption parameters under static skin contact

Publications based on this chapter:

Raccuglia M, Hodder S, Havenith G, (2016) Human wetness perception in relation to textile water absorption parameters under static skin contact. *Textile Research Journal.*

CHAPTER SUMMARY

In this study, we showed, in static skin contact conditions, the role of fabric thickness as a major determinant of fabric absorption capacity, independently of fibre type. Nevertheless, the impact on absorption was not investigated. Furthermore, in fabrics wetted according to their absorption capacity (same amount of moisture per volume) the perception of wetness was positively related to fabric thickness. Even in this case, the relation between fabric thickness and wetness perception was independent of fibre type. In fact, when matching for thickness parameters, wetness perception was not different between cotton and polyester materials, neither between different polyester blends. As such, in conditions where fabrics are in static contact with the skin, fabric thickness was indicated as a major factor predicting absorption capacity and also wetness perception. Furthermore, in these conditions sensations of discomfort increased with the increase in fabric wetness perception. The second aim of this study was to study different approaches to characterise fabric moisture content, i.e. absolute (same µL of water per area (cm^2)) versus relative (same µL of water per unit of fabric volume (cm^3)). In fabrics presenting same saturation percentage (same water content per volume) a positive relation between fabric thickness and wetness perception was observed and it was independent of fibre type. When applying the same relative to volume water content (same saturation percentage) thicker fabrics were perceived wetter than the thinner ones. Conversely, when applying the same absolute water amount, thicker fabrics were perceived dryer compared to thinner fabrics, given that thinner fabrics were more saturated. These findings indicated that human wetness perception responses between fabrics with different volume/thickness parameters should be interpreted in light of their saturation parameters rather than considering the absolute moisture content.

3.1 Introduction

The haptic perception of wetness while wearing clothing represents one of the most critical factors contributing to thermal and sensorial discomfort during wear (Li 2001, 2005; Fukazawa and Havenith 2009). It has been acknowledged that, despite the ability to perceive wetness, the human skin is not provided with specific hygro-receptors (Clark and Edholm 1985). Therefore, the study of human wetness sensation has attracted many researchers from multiple disciplines (Bentley, 1990; Fukazawa and Havenith 2009; Ackerley et al. 2012; Bergmann Tiest et al. 2012; Filingeri and Havenith 2015). Regarding the modality in which humans perceive moisture and humidity, recently it has been proposed that the perception of wetness is based on a multimodal integration of thermal and mechanical inputs occurring at the skin, when it is wet (Filingeri et al. 2014a; Filingeri and Havenith 2015).

With regards to textile materials, which often come in contact with the human body, the level of wetness is not an intrinsic property of the material in itself, such as texture or temperature, but is defined by the combined effect of the amount of liquid present in the fabric (e.g. sweat rate, rain) and on the ability of the fabric to absorb moisture, i.e. hygroscopicity. The majority of the studies available that have investigated the mechanisms underlying the ability to perceive wetness have often neglected the contribution of fabric properties and our knowledge on how these modulate wetness perception is still limited. On the other hand, the study of how textile parameters affect moisture absorption has received great attention within the context of wear comfort, over the past years. Fourt et al. (1951) compared water absorption and drying properties of synthetic fabrics with conventional wool and cotton. They found that, regardless of fibre type, all fabrics absorb water and drying time is proportional to the amount of water initially absorbed, rather than related to fibre type. In support, Crow and Osczevski (1998) found that the amount of water absorbed by fabrics with different fibre type was correlated to the fabric thickness ($r = 0.92$) and a strong correlation was also observed between the amount of water absorbed and the drying time ($r = 0.98$); the correlation was independent of fibre type (Crow and Osczevski, 1998). Furthermore, Yoo and Barker (2004) indicated that the total amount of liquid absorbed does not change in relation to the fibre type and the difference between fabrics with different hydroscopicity is in the rate of water absorption, rather than the total amount of water absorbed.

In wear trials, where sweat absorption occurs from the skin, Holmér (1985) observed that a clothing ensemble made of wool absorbed more sweat than a nylon one: 245 g versus 198 g, respectively. This variation could be linked to differences in sweat production between the two clothing ensembles, rather than to the fibre hygroscopicity. In fact, in Holmér's study, although fabric thermal resistance and clothing insulation was very similar (and probably fabric thickness, although it was not specified) between the wool and nylon clothing system, participants presented higher sweat production in the wool condition compared to the cotton condition (759 g versus 702 g), during running.

In the past the majority of the researchers have mainly focused on comparing natural and synthetic fibre, and less on how other fabric factors affect water absorption properties and the related wetness perception. In a human sensorial trial, where fabric water content was manipulated, a wool and a polyester fabric, applied on the inner forearm, resulted in different wetness perception, despite the application of the same relative moisture levels of 0, 2, 4, 10 and 15% (excess of fabric conditioned weight). In particular the wool was perceived dryer than the polyester fabric at each moisture level (Li et al. 1992b). In a human sensorial trial also Plant et al. (1995) studied the effect of fibre type on wetness perception by adding 4 relative levels of water (2, 4, 8 and 16% of the fabric conditioned weight, in equilibrium regain) and found that wool and cotton fibres are perceived significantly dryer than polyester. Focusing on other fabric properties, Tang et al. (2014) found that thinner fabrics are perceived significantly wetter than thicker fabrics, explaining the observed relation with fabric thickness. In this experiment, given that the same absolute amount of water was added to the experimental fabrics, thinner fabrics presented higher relative water amount to textile volume-ratios, compared to the thicker samples. The latter could have been the reason for thinner fabrics being perceived wetter. Hence, due to these thickness-related differences in fabric total water content and wetness perception, Tang's et al. (2014)

results may not be applicable if a water amount relative to fabric volume (same μl.mm^{-3} rather than μl.mm^{-2}) is applied.

Against the aforementioned research background, both thickness differences and the modality in which fabric moisture content is manipulated should be taken in into account when studying fabric moisture properties and the related wetness perception. In the current study, in order to correct for volume-related differences in wetness perception that could occur during the application of the same absolute (μl.mm^{-2}) water content, fabrics wetness perception was studied under the same relative to volume water content (i.e. μl of water per mm^3 of fabric) and compared with the application of the same absolute water content (i.e. μl of water per mm^2 of fabric). Additionally, the contribution of thermo- and mechano-sensitivity on the ability to discriminate various degrees of wetness in different fabrics was studied through analysis of local skin temperature changes and the impact of various fabric weights. Finally, to minimise the role of physical surface characteristics on the perception of wetness, fabrics were assessed under static contact with the skin. The aim of this study was threefold: 1) to examine the role of thickness and fibre type on fabric absorption capacity and wetness perception; 2) to investigate the contribution of fabric mechanical and thermal inputs on wetness perception; 3) to compare wetness perception outcomes between two different wet states, i.e. same absolute (μl.mm^{-2}) versus same relative (μl.mm^{-3}) water content.

3.2 Method

3.2.1 Specimen

Twenty-four knitted fabric samples (100 x 100 mm) selected for different structure, thickness and fibre type were included in this experiment. Details and specifications of the testing samples are summarized in table 1.

Table 1 Details and specifications of the experimental fabrics. Data are reported as mean ± standard deviation.

Fabric code	Structure	Material	Thickness (mm)	Weight (g/m²)	100% absorption capacity (µl)	100% REL (µl.mm⁻³)
F1	single jersey	100 % cotton	0.62 ± 0.014	140 ± 0.012	4793.3 ± 0.495	0.773
F2	warp knit tricot (double)	80 % nylon/20 % elastane	0.67 ± 0.022	190 ± 0.006	4742.0 ± 0.566	0.708
F3	interlock (1x1 both sides)	100 % polyester	1.20 ± 0.014	255 ± 0.01	8763.0 ± 1.062	0.730
F4	spacer knit-3 layers (triple)	95 % polyester/5 % elastane	2.80 ± 0.005	270 ± 0.025	21710.0 ± 0.354	0.775
F5	double jersey	100 % cotton	1.00 ± 0.01	280 ± 0.037	7950. 7 ± 0.566	0.795
F6	2x2 rib	97 % cotton/ 3 % elastane	1.30 ± 0.018	385 ± 0.035	9534.3 ± 0.846	0.733
F7	unbrushed, french terry (tuck & miss on reverse)	100 % cotton	2.10 ± 0.02	330 ± 0.001	13992.7 ± 1.556	0.666
F8	brushed, french terry (tuck & miss on reverse)	100 % cotton	3.50 ± 0.028	330 ± 0.029	24769.0 ± 0.495	0.708
F9	brushed both sides, french terry (tuck & miss on reverse)	100 % polyester	4.00 ± 0.037	290 ± 0.023	33535.0 ± 0.354	0.838
F10	brushed both sides, french terry (tuck & miss on reverse)	100 % polyester	1.50 ± 0.06	185 ± 0.049	11000.0 ± 0.254	0.733
F11	pique (knit & tuck)	100 % polyester	0.60 ± 0.058	130 ± 0.047	4207.7 ± 0.566	0.701
F12	warp knit plus brush one side	100 % polyester	0.90 ± 0.02	130 ± 0.023	6624.7 ± 0.778	0.736
F13	single jersey	82 % nylon/ 18 % lycra	0.32 ± 0.009	120 ± 0.05	2673.3 ± 1.626	0.835
F14	single jersey mesh	92 % polyester/ 8 % spandex	0.70 ± 0.025	223 ± 0.023	5828.3 ± 1.061	0.833
F15	single jersey	94 % polyester/ 6 % lycra	0.60 ± 0.011	151 ± 0.04	3535.0 ± 0.919	0.589
F16	double jersey pique	100 % polyester	0.65 ± 0.025	148 ± 0.052	5844.0 ± 0.636	0.899
F17	double jersey pique	100 % polyester	0.56 ± 0.03	160 ± 0.095	4404.0 ± 0.495	0.786
F18	single jersey	100 % polyester	0.30 ± 0.012	74 ± 0.054	2471.3 ± 0.283	0.824
F19	double jersey	100 % polyester	0.50 ± 0.001	130 ± 0.012	3954.0 ± 0.495	0.791
F20	single jersey	92 % polyester/ 18 % elastane	0.60 ± 0.024	200 ± 0.052	4769.7 ± 0.495	0.795
F21	single jersey	88 % polyester/ 6 % wool/ 6 % spandex	0.66 ± 0.042	192 ± 0.09	5559.3 ± 0.283	0.842
F22	single jersey pique structure	83 % coolmax air/ 17 % polyester	0.60 ± 0.01	153 ± 0.047	5036.3 ± 0.495	0.839
F23	single jersey	83 % coolmax air/ 17 % polyester	0.56 ± 0.023	160 ± 0.029	5164.0 ± 0.424	0.922
F24	double jersey	60 % polyester/ 40 % polypropylene	0.60 ± 0.01	142 ± 0.029	5270.3 ± 0.849	0.953

3.2.2 Wetting procedure

Fabrics were wetted 30 min before each experimental trial, in accordance to the balanced order of application during the human sensorial assessment. Each fabric was positioned onto a plastic film and water was added by using a micropipette (SciQuip LTD, Newtown, UK) positioned at a fixed distance of 10 cm perpendicular to each sample and pointing at its centre. When the water was in equilibrium with the fabric, (specifically, when the water spread out uniformly across the sample; this took approximately 1 minute) each fabric was placed into a plastic bag which was securely sealed to prevent water evaporation. No water dripped from the samples inside the plastic bags during the storage period. The fabric wetting procedure was the same for all the conditions (100REL, 50REL and ABS) and only differed in the amount of added water. During the application period on the skin, each fabric was covered with a PVC film on the outer side to prevent evaporation of water.

Fabrics were tested at same relative (to volume) water content (REL; $\mu l.mm^{-3}$) and at same absolute water content (ABS; $\mu l.mm^{-2}$). Within the REL condition two different amounts of water were applied to simulate heavy and moderate sweating conditions: 100% of fabric absorption capacity (100REL) and 50% of fabric absorption capacity (50REL), respectively. The relative water content for the 100REL condition was calculated according to:

$$\text{100REL } (\mu l.mm^{-3}) = 100\%\ absorption\ capacity\ (\mu l)/fabric\ volume(mm^3)$$

The relative water content for the 50REL condition was calculated according to:

$$50\text{ REL } (\mu l.mm^{-3}) = (100\%\ absorption\ capacity\ (\mu l) * 0.5)/fabric\ volume(mm^3)$$

Water absorption capacity (100%) was determined according to the 'water absorption capacity test' described by Tang et al. (2014a). For the test a fabric sample (100 x 100 mm) was put into a tank of water and 5 minutes was allowed for it to sink completely into water. Following from this, the fabric was taken out by tweezers and hung onto a rod vertically until there was no water dripping within a 30 seconds interval. The water gain was calculated according to:

$$Water\ absorbed\ (\mu l) = [wetF\ (g) - dryF\ (g)] * 1000\ \frac{\mu l}{g}$$

Where,

wetF, is the weight of the saturated fabric (g);

dryF, is the weight of the dry fabric (g).

The range of fabric water absorption capacity was 2500-33500 µl (Table 1). The average amount of water per unit volume of fabrics (µl.mm^{-3}) for both 100REL and 50REL was 0.8 ± 0.08 µl.mm^{-3} (Table 1) and 0.4 µl.mm^{-3}, respectively.

For the ABS condition a total amount of water of 2400 µl was added to all of the experimental fabrics, corresponding to 0.24 µl.mm^{-2} and translated into water content per volume to the range of 0.06-0.8 µl.mm^{-3}.

Additionally, to test whether other fabric properties, i.e. thermal conductivity or regain, could affect fabric wetness perception under the three wet states, the fabric samples were also tested under dry state (DRY). In the DRY condition 7 wet stimuli (F1, F3, F4, F8, F14, F18, F19) were included to prevent misleading responses due to the repeated presentation of the same (dry) stimulus (i.e. habituation to the stimulus).

3.2.3 Weight differences correction

In order to eliminate the contribution of fabric weight pressing on the skin on the perception of wetness, in the 50REL condition a subset of 7 fabrics (F1, F3, F4, F8, F14, F18, F19), wetted according to their 50% absorption capacity, were all brought to the same wet weight ($50RELW_{corr;}$ same weight, different absolute water content). In order to correct for weight differences, the heaviest wet fabric (F8) of 18 g was chosen as reference and the remaining 6 fabrics were adjusted to this weight (18 g), by adding extra weight (layers of dry fabrics) on top (outside) of the experimental wet fabric, according to:

$extra\ weight = 18g - wet\ fabric\ weight.$

The extra layers of dry fabrics were separated from the experimental wet fabric via means of a PVC film, to prevent water transfer from the wet fabric to the dry layers.

The $50RELW_{corr}$ fabrics were also compared with the corresponding 50REL fabrics tested in standard condition (same absolute water content, different weight) ($50RELnoW_{corr}$).

Below summarised the five experimental conditions:

100REL= 100% fabric absorption capacity (0.6-0.9 $\mu l.mm^{-3}$).

50REL= 50% fabric absorption capacity (0.3-0.45 $\mu l.mm^{-3}$).

$50RELW_{corr}$ = fabrics wetted according to their 50% absorption capacity, presenting different absolute water content but same total wet weight (18 g).

ABS= same total absolute water content (2400 $\mu l.mm^{-2}$);

DRY= equilibrium regain (no water added).

3.2.4 Fibre type

To study the effect of fibre type on wetness perception, 11 fabrics, matched for thickness, were grouped in three main clusters:

- Group 1 (0.60 mm): F11, F15, F20, F22, F24.
- Group 2 (2.10-2.80 mm): F4, F7.
- Group 3 (3.50-4 mm): F8, F9.

3.2.5 Participants

Twelve young (23.4 yrs. ± 2.4, 72.4 ± 6.4 Kg, 174.57 ± 6.9 cm), active (at least 4-6 hours per week) and with no history of sensory related disorders, male (7) and female (5) participants of Western European origin, volunteered to participate in this study. The test procedure and instruments were explained to each participant verbally and through a written information form. Following from this, participants gave written informed consent for participation. Participants were not informed regarding the aim of the study, experimental conditions (100REL, 50REL, $50RELW_{corr}$; ABS; DRY), magnitude of the stimulus (amount of water applied) and type of fabric. The protocol and procedures involved were approved by Loughborough University Ethics Committee. The study was conducted within the confines of the World Medical Association Declaration of Helsinki for medical research using human participants.

3.2.6 Study overview

Fabrics were assessed in four separated trials which differed in the amount of water applied: 100REL; 50REL; ABS; DRY. Fabrics were assessed by using a quantitative sensory test, which consisted of placing, in a balanced order, 24 fabrics with different wetness levels on the upper back of each participant. Participants reported their local wetness perception, thermal sensation and thermal comfort on interval scales (see Measurements section). Prior to the first experimental trial, participants were familiarised with the experimental protocol, procedures and instruments used in the present study. The first experimental trial was conducted immediately after the familiarization session. The trials were completed in a counter balanced order and all experiments were performed in a climate controlled room, maintained at air temperature 25 °C, relative humidity 50% and air velocity < 0.05 m/s.

3.2.7 Experimental protocol

In the four experimental trials, participants entered the controlled climatic room and lied prone on a bench wearing underwear only. A square of 100 x 100 mm was marked on the upper back of each participant, with the superior margin of the square in line with the inferior margin of the seventh cervical juncture, to identify the fabrics' area of application. Before being marked, the body area was cleaned with an alcohol pad, to ensure the skin was clean and free from grease. Participants were then instrumented with skin measurement systems (see Measurements section) and rested for 20 min to allow time for skin temperature, thermal sensation and thermal comfort to stabilise. After the stabilisation period the investigator applied two reference fabrics on the participants' upper back, each corresponding to one of the two extreme points on the wetness perception scale: 0 (extremely dry) and 30 (extremely wet). The score of each reference fabric was reported by the investigator which also informed the participant that the wetness intensity of the subsequent fabrics would not exceed the range of these two references. Following from this, each experimental fabric was applied on the participants' upper back for a period of 20 seconds. To prevent evaporation of water from the fabric and related cooling during the 20 seconds stimulation period, each experimental fabric, in all conditions, was covered by a PVC film. Participants were alerted by the investigator before the application of each fabric. At the end of the 20 seconds stimulation period, participants were encouraged to verbally report their wetness perception, thermal sensation and thermal comfort for the stimulated area, using the three interval scales. The scored fabric was then removed from the upper back and a dry cloth was placed onto the tested body area to avoid any chilly sensation, consequent to the evaporation of any remaining water on the skin. The tested body area was then gently wiped with the cloth and dried by blowing warm air; this took approximately 1 min and allowed temperature and hydration state of the skin to return to baseline before the application of the following experimental fabric. Additionally, since the continuous application of wet stimuli may decreases one's sensitivity, 1 min of rest, before the subsequent fabric application also allowed the recovery of the sensory system. The same protocol was repeated for each of the 24 fabrics and each trial took approximately 2 hours. Participants were instructed to ask for a rest whenever they felt uncomfortable.

3.2.8 Measurements

3.2.8.1 Skin temperature

Local skin temperature, before and after the contact with the fabrics, was measured by using a single spot infrared thermometer (FLUKE 566, Fluke Corporation, USA) with a temperature range of -40 to 800 °C and an intrinsic accuracy of ± 1 °C. During the testing the infrared thermometer was calibrated against a matte black plate whose temperature was monitored with a thermistor (Grant Instrument, Cambridge, UK) ensuring an increased accuracy of ± 0.2 °C.

Local skin temperature during the contact with each fabric was measured by using three fine wire Type T thermocouples (RS Components, Northants, UK) (with a response time to temperature changes lower than 0.1 second), applied on the tested body area (upper back) between the skin and the fabric. The thermocouples temperatures were monitored and recorded via a Grant Squirrel SQ2010 data logger (Grant Instrument Ltd., Cambridge, UK). Local skin temperature was calculated from the mean of the three measured spots. Before testing the thermocouples were calibrated by placing the measuring junction of each thermocouple in a circulating water bath whose temperature was monitored with a calibrated mercury thermometer.

Mean skin temperature was estimated from five sites, cheek, abdomen, upper arm, lower back, and back lower thigh, with iButtons wireless temperature loggers (Maxim, San Jose, USA), according to the work of Houndas and Ring (1982).

$$\begin{aligned}&Mean\ Skin\ Temperature\\&\qquad = (cheek\ 0.07) + (abdomen\ 0.175) + (upper\ arm\ 0.19)\\&\qquad + (lower\ back\ 0.175) + (back\ lower\ thigh\ 0.39)\end{aligned}$$

3.2.8.2 Wetness perception

Based on a literature survey and extensive piloting a new ordinal wetness perception scale was developed for this study. Generally, visual analogue scales (VAS) are considered preferable when high resolution in the measurement of a particular sensation is needed. However, pilot testing for this study highlighted that the use of VAS made the scoring process difficult for the participants when a large number of stimuli (in our case 24) needed to be scored. In fact, the lack of numbers or descriptors between the two anchor points at the extremes of the VAS results in the absence of references that could be used by the participant to relate a score to the previous given scores, the latter facilitating the judgement of the next stimulus an so on. On the contrary, Likert scales have the benefit of presenting descriptors, although these types of scales are usually characterised by no more than 9 descriptors, resulting in a significantly lower resolution compared to the VAS. In the current study, due to the large number of wet stimuli (24 different wet samples) a high level of resolution was needed. This was achieved through the design of a 30 points scale. The scale ranges from 0 to 30 (Fig 1: A) and each point corresponds to a specific number. Points 0, 5, 10, 15, 20, 25 and 30 are linked to descriptors to guide the assessors during the scoring process. The criteria for the development of the scale were applied based on the results from extensive pilot testing. For instance, a number of 7 wetness descriptors was chosen based on the relatively large range of physical wetness that was added to the experimental fabrics (ABS, 50 % saturated and 100% saturated). Additionally, each descriptor was divided into 5 different points to allow a gradual change from one to another descriptor and also to give to the participants the possibility to discriminate between small changes within the same descriptor.

3.2.8.3 Thermal sensation

For the same reasons presented above, a new ordinal thermal sensation scale was developed (Fig 1: B). The thermal sensation scale is a bipolar unbalanced scale presenting a central neutral point (0 = neutral), with 10 positive numbers (from 1 to 10) above and 15 negative numbers (from -1 to -15) below. Point 5 and 10 are linked to the thermal descriptors slightly warm and warm, respectively, whereas the negative numbers -5, -10 and -15 are linked to slightly cool, cool and very cool, respectively.

3.2.8.4 Thermal comfort

To assess fabrics' thermal comfort, a coarser scale was chosen, given that pilot studies for this experiment showed that the static interaction between the fabrics and skin does not greatly affect thermal comfort. Thermal comfort scale is a 7 point interval scale ranging from 1 to 7 with descriptors at point 1, 3, 5, 7 (Fig 1: C).

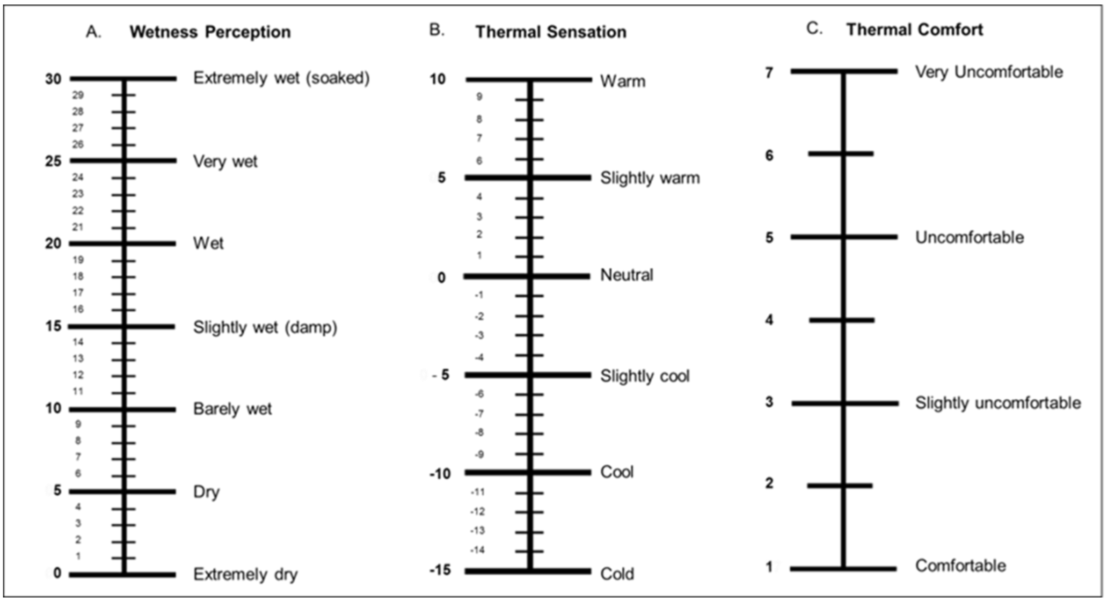

Figure 1A Wetness Perception scale; **1B** Thermal sensation scale; **1C** Thermal Comfort scale.

3.3 Statistics

In this study the independent variables were: fabric fibre type, fabric thickness, fabric absorption capacity, fabric water content and therefore fabric wet weight. Dependent variables were: local skin temperature drop, wetness perception, thermal sensation and thermal comfort.

Data were tested for normality of distribution with Shapiro-Wilk test and Normal Q-Q plot.

Kendall Coefficient of Concordance test (Kendall´s *W*) was conducted to assess the degree of agreement between participants (inter-judges reliability) in ranking the various experimental fabric samples. Kendall´s *W* ranges are (Fleiss et al. 2003):

- < 0.40, poor;
- 0.40-0.59, fair;
- 0.60-0.74, good;
- > 0.74, excellent.

Regression analyses were performed to study relationships between and within dependent and independent variables. Regression analyses were conducted by using data from group means.

To assess the effect of fabric fibre type on wetness perception a Friedman test was conducted for fabric group 1 (5 levels of comparison) and a Wilcoxon Signed Rank test was conducted for fabric group 2 (2 levels of comparison) and group 3 (2 levels of comparison). In group 1, when significant effects were identified, *post hoc* analysis was conducted by Wilcoxon Sign Tank test.

A Friedman test was also conducted to test whether there were differences in wetness perception responses within the $50RELW_{corr}$ fabrics (fabrics corrected for weight differences). When significant effects were identified, *post hoc* analysis was conducted by Wilcoxon Sign Tank test. A Wilcoxon Signed Rank test was conducted to assess whether wetness perception of each fabric was significantly different between $50RELW_{corr}$ and $50RELnoW_{corr}$ condition.

Finally, rank analysis was performed to compare wetness perception outcomes between the two wet conditions: 50REL and ABS condition. F1, F11, F15, F20, F22, F24 presented the same total water amount of 2400 µl in both 50REL and ABS, therefore these fabrics were not used for the above mentioned comparison.

In all analyses $p < 0.05$ was used to establish significant differences. Data are reported as means ± standard deviation (SD). Data were analysed by using the software IBM SPSS Statistics (version 22) (IBM, USA).

3.4 Results

3.4.1 Between-participants consistency

In order to eliminate individual discrepancy, the agreement in the ranking of the wetness intensity of the experimental fabrics was examined. Kendall´s *W* for the between participants effect was 0.762 at $p < 0.01$, meaning that the agreement between the 12 participants was higher than it would be by coincidence and indicating excellent agreement between participants (Fleiss, 1981).

3.4.2 Dry condition

In one of the four experimental trials fabrics were tested under dry state (DRY), to ensure that there were no differences in fabrics wetness perception, due to other fabric properties, i.e. thermal conductivity and regain. In DRY condition fabrics were all perceived below 5 (dry) and were not significantly different ($p > 0.5$).

3.4.3 Fabric thickness and fibre type

Analysis of the relationship between fabric absorption capacity and fabric thickness indicated that fabric thickness accounted for the 98 % ($r^2 = 0.98$) of the variability in fabric absorption capacity, despite differences in fibre content (Fig 2: A).

Fabrics typically used for sport T-shirts, in the thickness range of 0.30-1.00 mm, were considered separately also. Similarly in this fabric group a strong linear relationship between fabric thickness and fabric absorption capacity ($r^2 = 0.84$) was found (Fig 2: B).

When matched for thickness differences, different fibre types did not result in significantly different wetness perception outcomes (group 1 $p = 0.22$; group 2 $p = 0.47$; group 3 $p = 0.32$) (Fig 3). In group 1 (0.60 mm) only F15 was significantly different ($p = 0.006$) from F11, F20, F22, F24 (Fig 3).

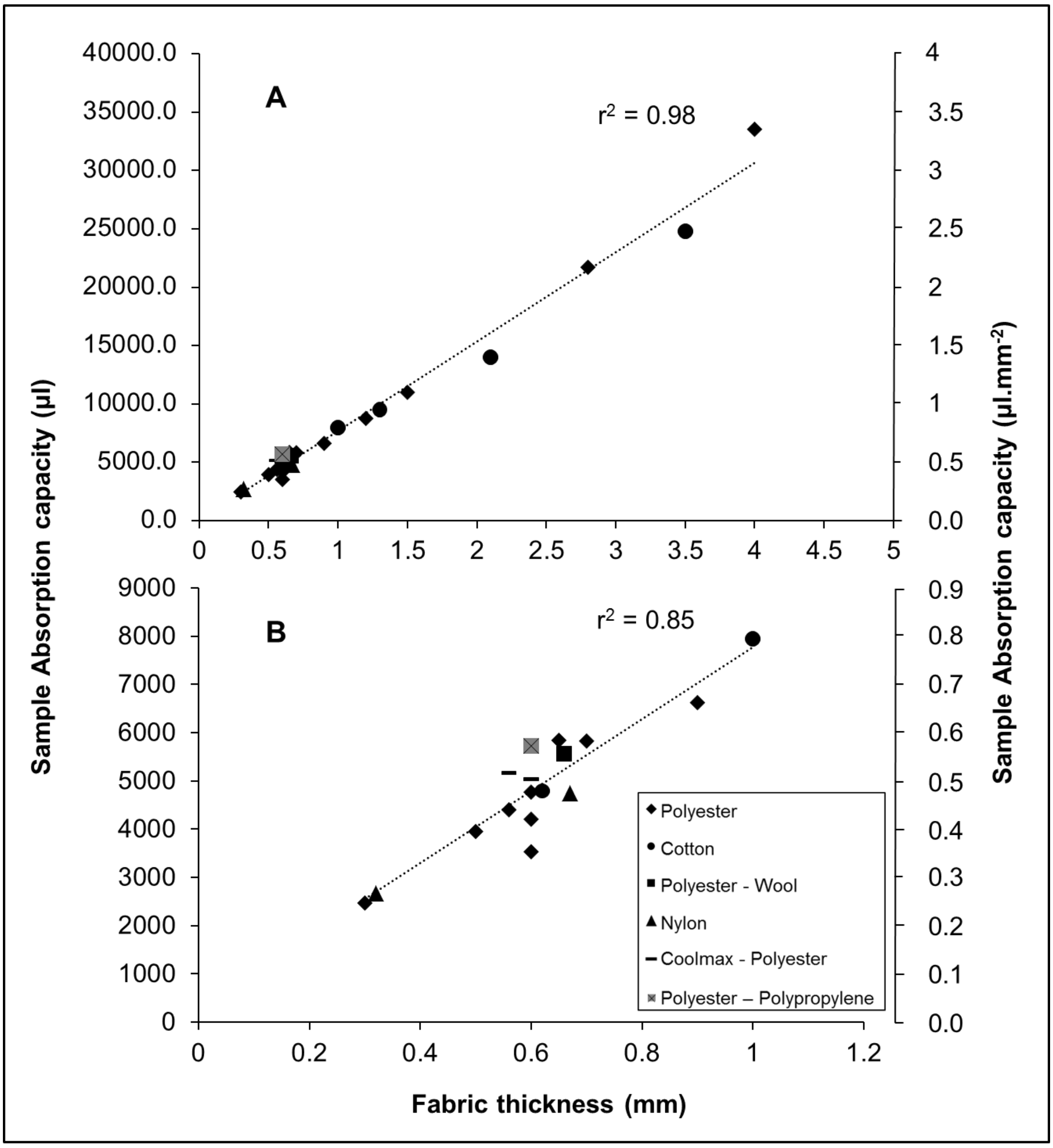

Figure 2A Relationship between fabric absorption capacity and fabric thickness for the 100 x 100 mm fabric samples. **2B** Relationship between fabric absorption capacity and fabric thickness for the fabric group characterised by a thickness range between 0.3 mm and 1.00 mm.

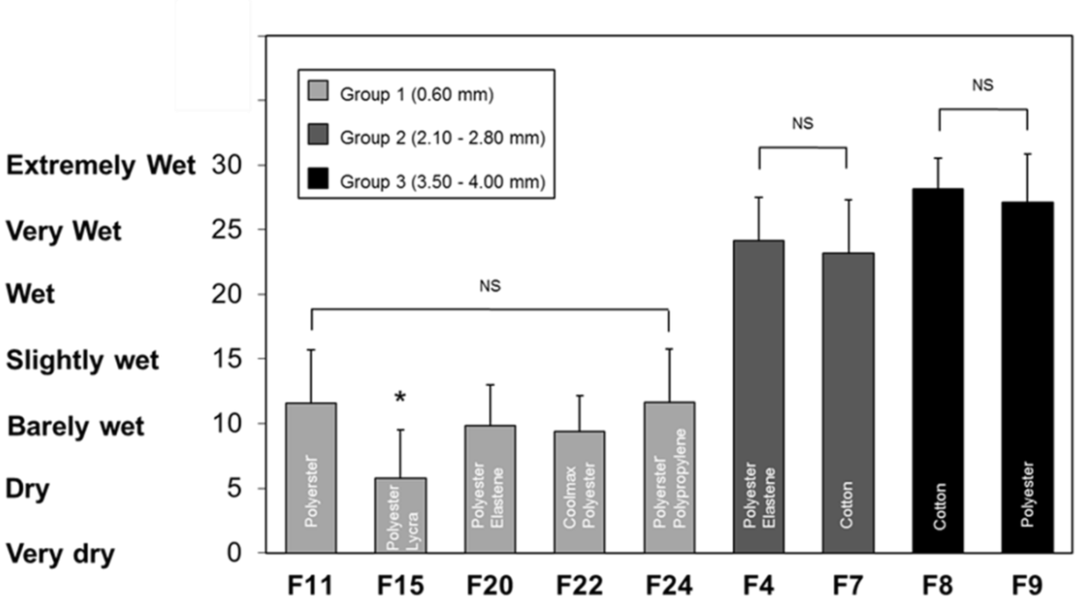

Figure 3 Effect of fibre type on wetness perception responses for the three groups of fabrics, grouped according to their thickness. There were no significant (NS) differences ($p > 0.05$) in wetness perception between F4 and F7 (group 2; thickness range between 2.10 mm and 2.80 mm), between F8 and F9 (group 3; thickness range between 3.50 mm and 4.00 mm), and between F11, F20, F22 and F24 (group 1; thickness of 0.60 mm). * In group 1, F15 resulted in a significantly lower wetness perception ($p < 0.05$) compared to F11, F20, F22 and F24.

3.4.4 Mechanical and thermal inputs on fabric wetness perception

Wetness perception at both 100REL and 50REL was plotted against the total amount of water presented in the fabrics (Fig 4). Results indicated that wetness perception showed a strong positive relationship (non-linear, second order polynomial) with fabric total water content in both 100REL ($r^2 = 0.82$, $p < 0.001$) and 50REL ($r^2 = 0.87$, $p<0.001$). In 100REL the regression curve shows a plateau above 15000 µl, suggesting a limit above which participants cannot perceive differences in fabrics water content.

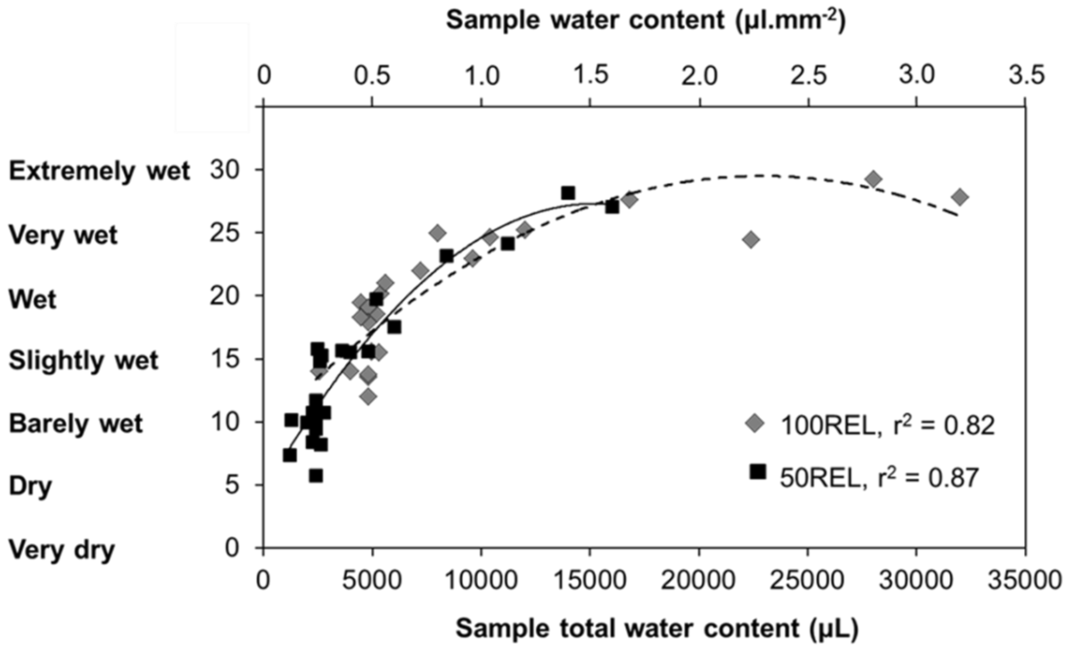

Figure 4 Relationship between fabric total water content and wetness perception in both relative experimental conditions: 100% of fabric water absorption capacity (100REL) and 50% of fabric absorption capacity (50REL). Due to the high correlation of thickness to absorption capacity, water content per volume of fabric was similar for all fabrics within each condition.

When looking at the effect of fabric weight on wetness perception the $50RELnoW_{corr}$ fabrics (Fig 5; grey bars; same relative water content, different absolute water content, different weight) showed the same results as in fig 4, i.e. higher wetness perception scores in fabrics with higher total water content and therefore weight ($p < 0.05$). In the 50REL condition where the skin pressure for all fabrics was the same ($50RELW_{corr}$), achieved by correcting the weight of the fabrics to the same value as F8 (Fig 5; black bars; same relative water content, different absolute water content, same weight), different wetness perception scores were still observed ($p < 0.05$), i.e. higher wetness in fabric presenting higher water content, despite same skin pressure. However, when each $50RELnoW_{corr}$ (lighter) fabric was compared with the corresponding $50RELW_{corr}$ (heavier), both presenting same absolute and relative water content, the $50RELW_{corr}$ fabric was perceived always as wetter ($p < 0.001$) than the $50RELnoW_{corr}$, i.e. at same absolute and relative water content (same fabric volume) wetness perception was increased by increasing the pressure on the skin (i.e. in heavier fabrics).

As expected, F8 was not significantly different between the two conditions ($p = 0.432$), given that it was chosen as reference (same skin pressure, as well as absolute and relative water content in both 50RELnoW$_{corr}$ and 50RELW$_{corr}$).

In 50RELnoW$_{corr}$ the magnitude of increase in wetness perception was related (non-linear relationship, second order polynomial, $r^2 = 0.8$, $p < 0.001$) to the amount of added weight (skin pressure increase) (Fig 6).

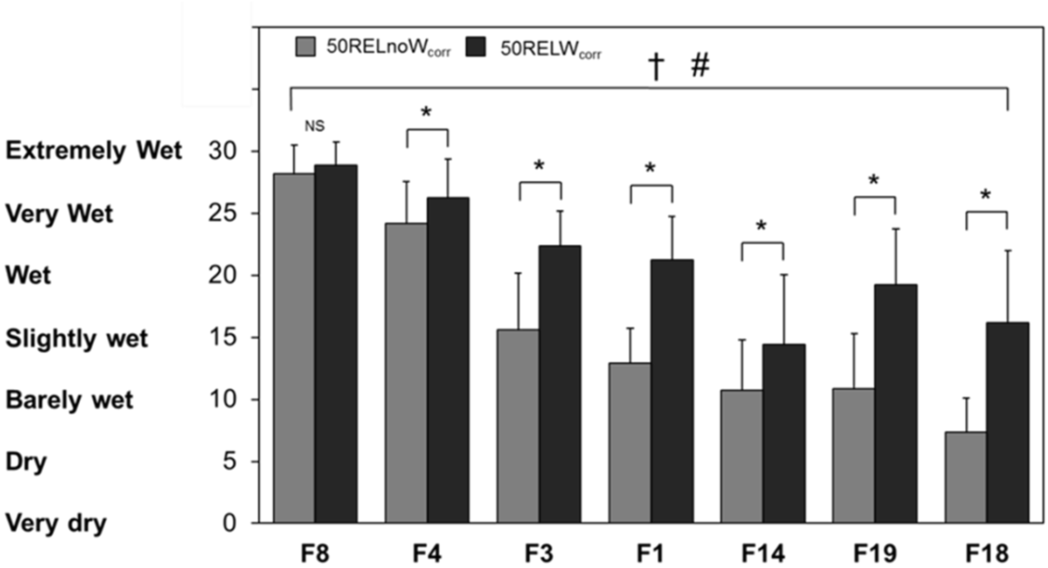

Figure 5 Fabric sorted from those containing the highest to those containing the lowest total water amount and therefore from the heaviest to the lightest fabric (F8-F18).

Significant differences ($p < 0.05$) in wetness perception responses between fabrics tested in standard condition (grey bars; 50RELnoW$_{corr}$).

† Significant differences ($p < 0.05$) in wetness perception responses between fabrics tested under same skin pressure (black bars; 50RELW$_{corr}$).

* Significant difference in wetness perception responses between the two skin pressure conditions 50RELW$_{corr}$ (higher skin pressure) and 50RELnoW$_{corr}$ (lower skin pressure).

No significant (NS) difference in wetness perception scores between 50RELnoW$_{corr}$ and 50RELW$_{corr}$ in F8 ($p = 0.43$).

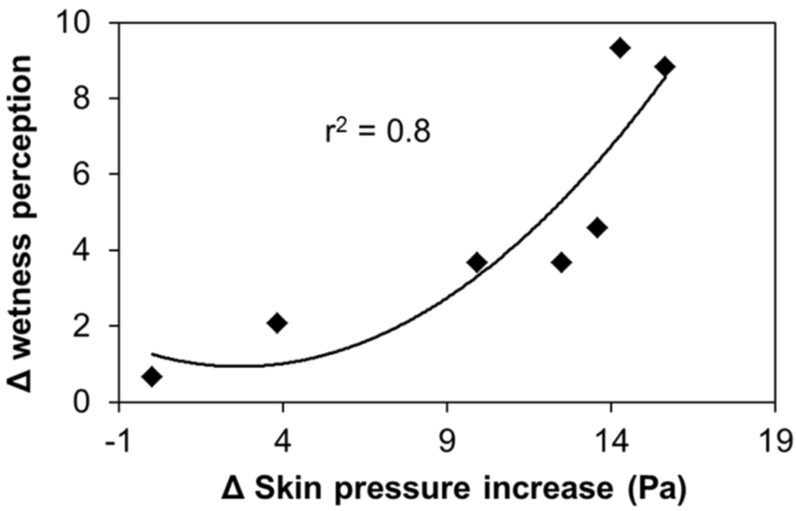

Figure 6 † Relationship between Δ Wetness perception (magnitude of increase from 50RELnoW$_{corr}$ condition) and the Δ Skin pressure increase (achieved by placing additional weight on each experimental fabrics in the 50RELW$_{corr}$ condition).

A non-linear (second order polynomial) relationship was found between decrease in local skin temperature (in response to the application of the wet fabrics) and fabric total water content in both 100REL ($r^2 = 0.74$, $p < 0.001$) and 50REL ($r^2 = 0.65$, $p < 0.001$) (Fig 7). The contribution of the thermal component on the perception of wetness was also indicated by the strong negative linear relationship between thermal sensation and wetness perception, in both 100REL ($r^2 = 0.80$; $p < 0.01$) and 50REL ($r^2 = 0.94$; $p < 0.01$) (cooler = wetter) (Fig 8: A).

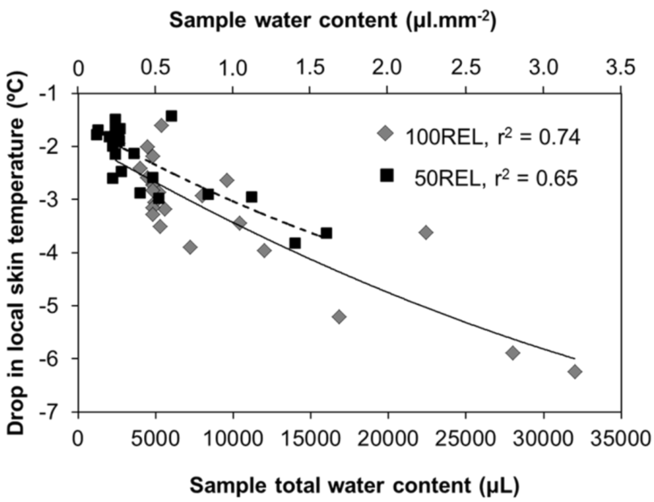

Figure 7 Relationship between fabrics total water content and decrease in local skin temperature, for both relative experimental conditions: 100% of fabric absorption capacity (100REL) and 50% of fabric absorption capacity (50REL).

Finally, a strong positive linear relationship was found between fabric wetness perception and thermal discomfort, in both 100REL ($r^2 = 0.86$; $p < 0.01$) and 50REL ($r^2 = 0.87$; $p < 0.01$) (Fig 8: B).

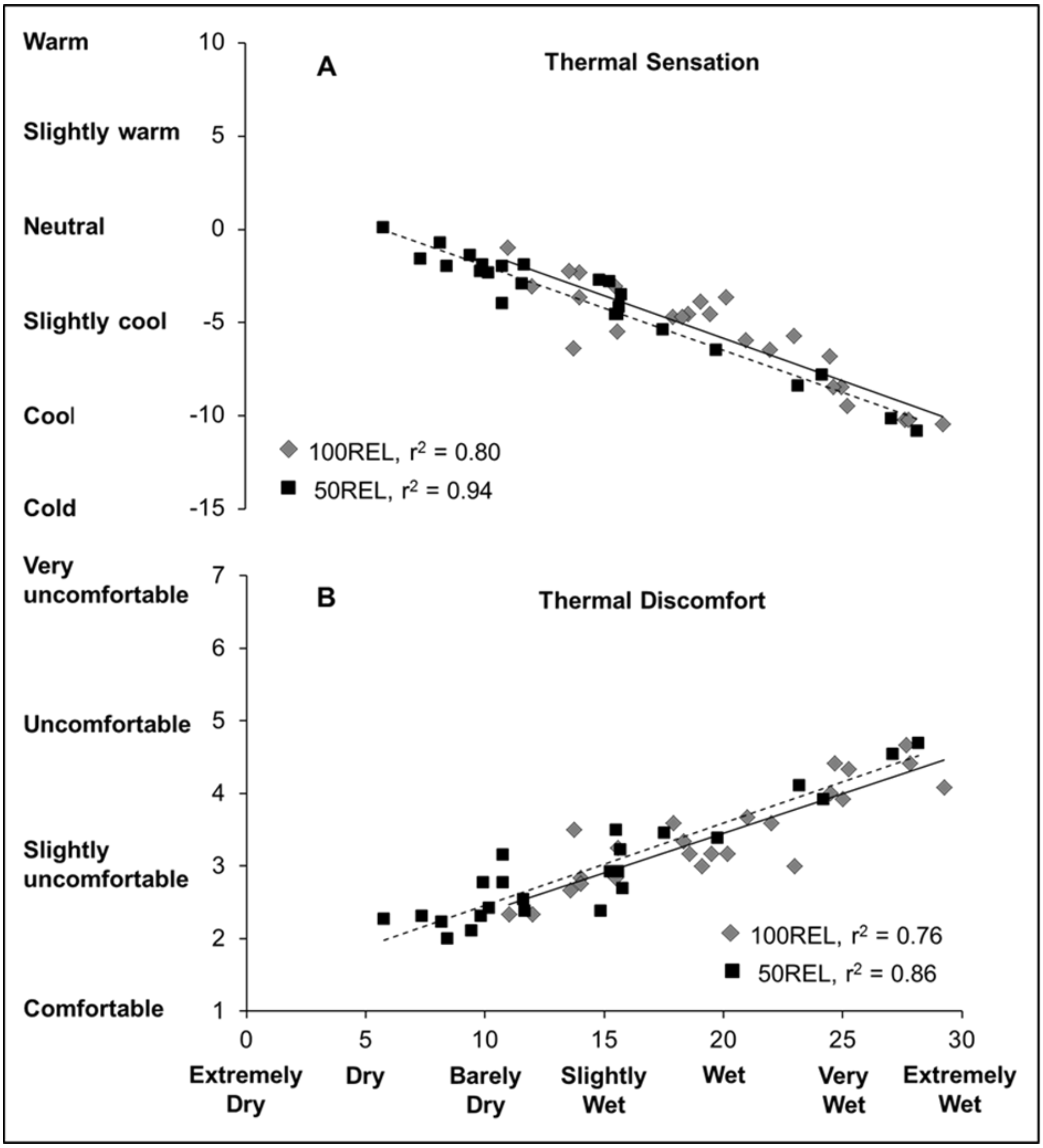

Figure 8A Relationship between wetness perception and thermal sensation, for both relative experimental conditions: 100% of fabric absorption capacity (100REL) and 50% of fabric absorption capacity (50REL). **8B** Relationship between wetness perception and thermal discomfort, for both relative experimental conditions: 100% of fabric absorption capacity (100REL) and 50% of fabric absorption capacity (50REL).

3.4.5.5 REL *versus* ABS water content

Wetness perception scores for both 50REL and ABS fabrics were converted into rank scores, on a scale from 1 (driest) to 18 (wettest) (Fig 9). The rank analysis indicated that in 50REL thinner fabrics (and thus having the lowest total amount of water and being the lightest) were ranked as driest, whereas in ABS thinner fabrics were ranked as wettest. The latter indicates that the two conditions lead to two opposite outcomes for the same fabric, in terms of wetness perception.

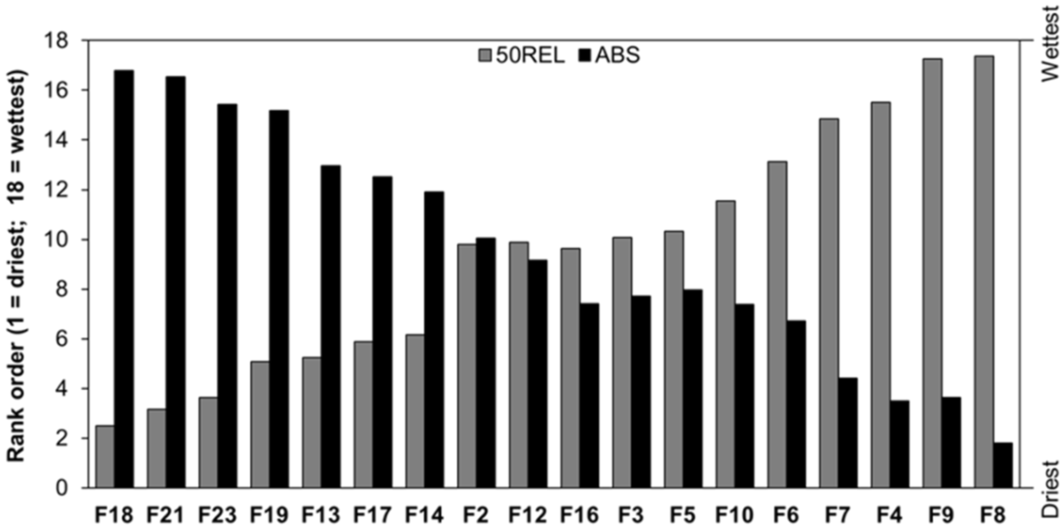

Figure 9 Rank order of wetness perception (0 = driest; 18 = wettest) for 18 fabrics in in both 50REL (similar µl.mm^{-3}) and ABS (same µl.mm^{-2}). On the x axis fabrics are sorted according to their rank (from driest to wettest) in 50REL.

3.5 Discussion

The present study demonstrated that fabric thickness is the major factor determining fabric absorption capacity, regardless of fibre type. Despite the absence of cutaneous hygro-receptors in the skin (Clark and Edholm 1985), participants were able to perceive different degrees of wetness. With regards to the contribution of textile factors on wetness perception, the results indicated that both fabric weight and cooling power provided mechanical and thermal cues. Both mechanical and thermal stimuli were determined by the total fabric water content (µl) and thus indirectly by fabric thickness which should be taken into account when studying fabric wetness perception. Finally, the use of two different approaches to manipulate fabric water content, i.e. relative to volume versus absolute per surface area, lead to contrary wetness perception outcomes for the same fabric.

3.5.1 Fabric wetness perception: thermal and mechanical contribution

In the REL condition, although fabrics were wetted with the same relative water amount (100% and 50% of fabric absorption capacity), participants were still able to discriminate between the different absolute water contents. According to Filingeri et al. (2013; 2014b) wetness is primarily perceived from thermal inputs occurring at the skin, with colder stimuli giving an illusory sensation of skin wetness and with pressure having a modulating effect. In the current study higher total water content provided higher skin cooling, which was sensed as greater changes in local skin temperature by the cutaneous thermoreceptors (Campero et al. 2001) and subsequently as higher wetness. Accordingly, Li (2005), in studying wetness perception of hydrophobic sweaters worn during walking under simulated rain, found that higher dampness scores were correlated with lower skin temperature. In the current study, the contribution of thermal inputs on the perception of wetness was indicated not only by the strong relationship between wetness perception and drop in local skin temperature, but also between wetness sensation and thermal sensation. The strong link between wetness perception and thermal sensation was also highlighted by Niedermann and Rossi (2012) who found that some fabric samples, previously wetted, were still perceived wet after a certain period of time, despite weight measurements indicating that no moisture was present. In their study the temperature of these samples was still below room temperature, due to the earlier heat transfer through evaporation, and this lower temperature could have suggested to the participants that the fabrics were still wet. It would be interesting to study whether by controlling for heat transfer-differences, related to different water contents, humans would still be able to discriminate between different degrees of wetness.

In the current study skin cooling mainly occurred through contact, given that water evaporation was prevented. In such a condition, cooling sensation increased with the increase in fabric thickness. However, it has been indicated that the real evaporative cooling is reduced when the distance between the skin and the locus of sweat evaporation (i.e. clothing) increases (i.e. less cooling is provided to the body per gram of evaporated sweat/moisture) (Havenith et al. 2013). Following on from this principle, Wang et al., (2014) indicated a linear reduction in real evaporative cooling with the increase of the garment thickness. Therefore, it is likely that at a specific saturation level and under condition of allowed sweat evaporation, thicker fabrics would result in lower cooling sensation and wetness sensation, because sweat would evaporate further away from the skin, providing less cooling power per unit of evaporated sweat to the skin.

In the current study results suggest that the wet weight of the fabric (mechanical stimulus) acting as load on the skin and sensed by the cutaneous mechanoreceptors (Tsunozaki and Bautista 2009), was also used by the participants as cue to perceive fabric wetness. When testing each of the 7 selected fabrics at two different skin pressures, i.e. $50RELnoW_{corr}$ (lower skin pressure) and $50RELW_{corr}$ (higher skin pressure), in the $50RELW_{corr}$ the resultant higher contact pressure on the skin resulted in higher wetness perception, despite each fabric presenting the same absolute ($\mu l.mm^{-2}$) and same relative (50REL; $\mu l.mm^{-3}$) water content in both conditions (Fig 5). The latter is likely due to the higher fabric-skin contact in the higher skin pressure condition, which increased the magnitude of stimulation of both cutaneous thermo- and mechanoreceptors. The higher stimulation resulted in an 'illusory' wetter perception which suggested higher water content in heavier fabrics. The latter highlights the contribution of mechano-sensitivity in perceiving various fabric moisture contents, which is in line with the neurophysiological model of skin wetness sensitivity proposed by Filingeri et al. (2014). In practice, this would translate into the use of lightweight garments, given that greater weight on the skin elicits wetter feelings.

3.5.2 Fabric thickness and fibre type

The results indicated that fabric thickness/volume is the major determinant of fabric absorption capacity (Fig 2: A and B). Given the strong correlation between human's wetness perception responses and fabric water content (mainly determined by fabric thickness), fabric thickness can be considered a critical factor to take into account when studying fabric wetness perception In the present study, under static contact with the skin, we did not observe an effect of fabric physical surface characteristics and fabric structure, though under dynamic contact this may be different. The latter will be addressed in a future investigation.

The strong correlation between fabric water content and thickness suggests that fibre type does not play a major role for this. In support, Yoo and Barker (2004) showed that fabric fibre type only affects water absorption rate but not the total amount of liquid absorbed in equilibrium. Absorption rate might play a critical role during the initial phase of sweat production, with hydrophilic fabrics taking moisture away from the skin quicker than hydrophobic ones, therefore resulting in dryer sensations during this initial timeframe. However, when sweat production increases and both the skin and the fabric become wet, the absorption rate is likely not to affect wetness perception and comfort responses. In support, our results showed that fabrics (wetted at 50% of their absorption capacity), with different fibre types but matched for thickness (therefore total water content) did not show differences in wetness perception scores (Fig 3). The latter suggests that fibre type in itself is not a determining factor for both fabric liquid absorption capacity and related wetness perception.

3.5.3 Same relative *versus* same absolute water content

The comparison between two different approaches to manipulate fabric water content, i.e. same relative to fabric volume (µL.mm^{-3}) versus same absolute to surface area (µL.mm^{-2}), showed two opposite wetness perception responses for the same fabric, due to thickness/volume-related differences (Fig 9).

The application of the same relative water content resulted in thinner fabrics being perceived dryer than the thicker ones. In fact, by applying the same relative water content, fabrics contained different total water amounts according to their volume, therefore thinner fabrics contained less water than the thicker in absolute terms. On the other hand, when applying the same absolute water amount, thicker fabrics were scored as dryer compared to thinner fabrics, given that thinner fabrics contained higher relative amounts of water to volume-ratio compared to the thicker fabrics, despite the same absolute water content (i.e. in thicker fabrics the same amount of water was spread over a larger volume).

These results indicate that the approach used to manipulate fabrics wet state should be carefully chosen with respect to the conditions to be represented. For instance, in a study assessing wetness perception of fabrics, unmatched for thickness, Tang et al. (2014) manipulated fabric wet state using an absolute water amount of 2400 µL per 14400 mm^2 (0.17µl.mm^{-2}). Under this wet state, thicker fabrics were perceived significantly drier than thinner fabrics (consistent with our results in ABS). Additionally, wetness perception responses were negatively correlated with fabric absorption capacity. Thus, in deciding which fabric is better (thin versus thick) for wetness perception one needs to consider the scenario of use. Results from the use of an absolute water amount may be representative of those exercise conditions that result in relatively low or mild sweat production, such as the initial phase of the work activity or relatively short-duration exercise performance. In these conditions the thinner material is likely to reach its saturation earlier than the thicker material, presenting higher relative to volume water content and higher wetness perception compared to the thinker one. Furthermore, in this scenario, according to the results from Tang et al. (2014) and our results in ABS, wetness perception negatively correlates with fabric absorption capacity. However, under higher sweat production conditions, e.g. when exercising in the heat or performing a prolonged exercise activity, the thicker material will also reach its saturation. In this scenario, despite the greater removal of sweat from the skin compared to the thinner material, the thicker fabric will present higher total water content, resulting in higher skin pressure and cooling capacity, both causing higher perception of wetness. Additionally, under this condition the correlation between fabric wetness perception and fabric absorption capacity will be positive, as we showed in the 100REL condition (Fig 4), rather than negative, as Tang et a. (2014) and we showed in the ABS condition. Finally, the use of a relative to volume water content may better represent post-exercise wetness perception responses, which are related to differences in fabrics drying time, mainly due to variations in fabric total water content (Crow and Osczevski 1998).

The application of the same absolute water content has led other researchers to interpret variations in fabrics wetness perception only in the light of fibre type-related differences. Niedermann and Rossi (2012), in studying the contribution of thermal cues on the ability to perceive different moisture contents, also applied the same absolute water content 2000 µL to three fabrics with a surface area of 2600 mm^2 ($0.77 µl.mm^{-2}$), different thickness and fibre type i.e. cotton (1.13 mm), polyester (0.89 mm) and synthetic blend (0.77 mm). At 5% and 95% dried state the cotton fabric was perceived significantly warmer and dryer than the polyester and synthetic blend fabric. In the study this variation in wetness perception was linked by the authors to fibre type-related differences between fabrics (Niedermann and Rossi 2012) rather than to volume-related differences. However, based on the present data, the latter explanation (different amount of water (µl) per volume (mm^3) seems more likely, given that the cotton fabric presented the highest thickness and therefore had a lower relative to volume water content.

Acknowledging the critical role of fabric thickness, it would be ideal to study wetness perception using fabrics matched for thickness characteristics. However, this is not always possible, especially in an industrial setting where comparisons of wetness perception responses of fabrics with different characteristics, thickness included, are conducted to identify the least uncomfortable material. In this situation, to prevent the introduction of biased conclusions related to differences in fabric thickness, we suggest that fabric wetness perception should be studied at both same relative to volume water content and absolute water content. The use of both approaches will allow the interpretation of the results with regard to the product application, i.e. low-mild sweat production or high sweat production activity. In addition, by taking into account the role of thickness on fabric water absorption and wetness perception, the application of relative water content to fabrics unmatched for thickness characteristics may potentially demonstrate the role (major, minor or interactive) of other factors, such fabric structure, surface geometrical features and fibre type.

Similarly, biased conclusions could be drawn when referring to threshold detection and different threshold of wetness perception in absolute terms. For instance, Sweeney and Branson (1990a) indicated that the absolute threshold of moisture detection is 0.024 ml. However, in this study always the same cotton/polyester blend fabric of 2580 mm^2 was used to detect the threshold of 0.024 ml of water, therefore this only applies to fabrics with a specific thickness range (not specified in their study). For instance, participants would probably not be able to detect the same amount of water of 0.024 ml in a thicker material, or conversely would perceive a smaller amount of water in a thinner fabric, given that the fabric would contain lower or higher relative to volume water content, respectively. On the other hand, Jeon at al. (2011) indicated that when applying a total water amount of 500 µl to a cotton and a high performance polyester fabric, both having a surface area of 10000 mm^2 (0.05 $\mu l.mm^{-2}$) the different threshold (the minimum amount of water change required to elicit a difference in wetness perception from 500 µl) is 252 µl of water for cotton and 193 µl for high performance polyester. However, even in this case, the latter may not apply to wider fabric thickness/volume range.

3.6 Conclusion

In conclusion, the present study confirmed the role of fabric thickness/volume as the major determinant of fabric water absorption capacity. In particular, fabric absorption capacity increases when fabric thickness is also increased, with no effect of fibre type, although fabric absorption rate was not investigated. Given the strong positive correlation between fabric absorption capacity and wetness perception, in the static condition used, fabric thickness thus represents an important parameter to take into account when looking at wetness perception of fabrics saturated, partially saturated or presenting the same absolute water content. Under static fabric-skin contact participants can perceive various degrees of fabric wetness by integrating fabric thermal (cooling provided) and mechanical (load on the skin) inputs sensed at the skin by thermo- and mechanoreceptors, respectively. Fabric thermal properties under wet state seem to be the main cues contributing to the perception of moisture content. Specifically, with the increase in fabric water content the cooling power, related to the heat capacity of the liquid in the textile, also increases, resulting in higher local skin cooling and wetness perception. The contribution of fabric mechanical input was indicated by greater wetness perception in heavier fabrics, due to the resultant higher load/pressure on the skin which increases the magnitude of stimulation of both thermo- and mechanoreceptors. In practice, factors like wet weight of the fabric and resultant local skin temperature drop should be taken into account when designing a garment with reduced wetness perception and related discomfort features.

To prevent the introduction of biased conclusions, due to thickness/volume-related differences in fabric wetness perception, we suggest that the methodology used to manipulate water content of fabrics with different thickness/volume, should be carefully considered in relation to the product end-use. In particular, the use of a relative to volume water content ($\mu L.mm^{-3}$) is recommended when evaluating fabric absorption property and related wetness perception of fabrics meant to be used for activity that induce high sweat production. In this context a saturated thick material would contain higher total water content (due to its higher volume) with higher wetness perception compared to the thin ones. Conversely, the application of an absolute water amount better represent fabric wetness perception outcomes occurring under activities characterised by low or medium sweat production, in which the thin material will reach saturation earlier than the thick ones (due to its smaller volume), with concomitant higher wetness perception. These approaches may be particularly useful for researchers investigating wetness perception and discomfort-related responses between fabrics unmatched for thickness and volume characteristics with regard to the specific exercise activity to be performed.

CHAPTER 4

Laboratory study 2

Human wetness perception of fabrics under dynamic skin contact

Publications based on this chapter:

Raccuglia M, Pistak K, Heyde C, Qu J, Mao N, Hodder S, Havenith G. (2017) Human wetness perception of fabrics under dynamic skin contact. *Textile Research Journal.*

CHAPTER SUMMARY

Moving forward from a study looking at the contribution of fabric thickness on wetness perception, in this study we assessed the role of fabric surface properties, in conditions of dynamic fabric-to-skin contact. It was observed that fabric materials with a smoother surface resulted in greater skin wetness perception compared to the rougher fabric surfaces. We proposed that, when moving across the skin, the wet smoother materials caused higher cutaneous displacement compared to the rougher ones. The higher skin displacement likely resulted from a higher adhesiveness between the wet fabric and skin, which in turn was caused by the creation of a greater number of contact points offered by the smoother fabric surface. In turn, the magnitude of skin displacement was detected by the cutaneous tactile receptors as stickiness or clinginess sensation and associated with the presence of a wet material on the skin. In the same study, we quantified fabric surface texture using the Kawabata Evaluation System to assess whether texture data can be used as predictors of fabric stickiness sensation and wetness perception. The results showed that the Kawabata evaluation system failed to predict stickiness sensation of wet fabrics commonly assumed to be associated with fabric texture. Thus, it was concluded that a different way to define fabric texture may be needed in order to represent this link (stickiness and texture). Although we did not find a relationship between fabric texture properties (measured with the Kawabata Evaluation System) and wetness perception/stickiness sensation, we could not ignore the strong positive relationship between stickiness sensation and wetness perception. Interestingly, the predicting power of wetness perception became stronger when including, together with stickiness, fabric thickness. This indicated that, in dynamic contact conditions, both stickiness sensation (theoretically fabric texture properties) and fabric thickness are important factors to consider when selecting fabrics for the development of next to skin clothing with improved moisture management properties. In fact, these two factors modulate cutaneous sensations of fabric wetness, which might ultimately contribute to the reduction in wear discomfort and overall discomfort.

4.1 Introduction

Whenever we increase our activity level and body heat content, sweat production causes moisture to build-up on the skin. The human ability to perceive skin wetness causes tactile and thermal discomfort (Fukazawa and Havenith 2009), this driving behavioural thermoregulatory responses (Schlader et al. 2010) aimed at maintaining homeostasis, ensuring health and survival (Parsons 2014). In absence of visual or auditory cues, skin wetness is perceived via learning processes (Bentley 1900) and through the central integration of thermal and mechanical stimuli occurring at the skin (Bergmann Tiest et al. 2012; Filingeri and Havenith 2015).

A large body of research has been focusing on the complex multisensory modality of wetness perception using fabrics (Sweeney and Branson 1990a; Sweeney and Branson 1990b; Jeon et al. 2011; Niedermann and Rossi 2012). For instance, Li (2005), in wear trials, and recently Raccuglia et al. (2016), in local body sensorial trials, highlighted the contribution of cold sensation to the perception of fabric moisture. Specifically, in both studies greater wetness perception was observed in response to greater reduction in skin temperature, which in return was affected by fabric water content. By studying the contribution of each single sensory modality (thermo- and mechano- sensation), Bergman Tiest et al. (2012) concluded that when interacting statically with a wet fabric the only cue available to perceive wetness is the thermal one. Conversely, it has been recently shown that some mechanical cues (fabric pressure on the skin) also affect perceived wetness in static contact (upper back) (Raccuglia et al. 2016). In fact, in heavier fabrics the higher resultant skin pressure causes higher wetness perception responses, compared to lighter fabrics, despite having the same water content (Raccuglia et al. 2016). On the other hand, under dynamic contact (fabric manipulation) the mechanical cue, i.e. stickiness, can improve a person’s ability to discriminate various wetness intensities (Bergmann Tiest et al. 2012b).

The neurophysiological basis of wetness perception has been well documented in the classical work conducted by Bentley (1900), and has seen a revival in the last decade (Bergmann Tiest et al. 2012; Filingeri and Havenith 2015). However, in order to improve moisture sensation and thermal comfort of clothing it would be of great value to identify the textile parameters that trigger cutaneous thermal and mechanical inputs underpinning wetness perception. In addition, as single textile properties have often been defined using a whole range of physical tests, it would be of practical value to know which of these test parameters has the best predictive power for wetness perception. Only recently, the role of fabric thickness as factor determining wetness perception in saturated or in part saturated fabrics, under static skin contact has been demonstrated (Raccuglia et al. 2016). Nevertheless, under dynamic contact other fabric parameters might also play a role. In dynamic conditions the presence of moisture increases fabric to skin friction (Gwosdow et al. 1986; Kenins 1994; Sivamani et al. 2003), sensed as higher stickiness and used as cue to perceive wetness.

The mechanical and surface properties of fabrics have been studied in the context of end-users choice and satisfaction, leading to a series of investigations looking at the relation between objective and subjective assessments (Alimaa et al. 2000; Cardello et al. 2003a; Sular and Okur 2007). On the other hand, in the current study fabric texture properties will be evaluated to assess whether these influence the tactile cues underlying skin wetness perception. In this scenario, we hypothesised that, due to a greater number of contact points with the skin, fabrics with smoother surface texture will cause higher skin friction and/or displacement and will be perceived as wetter than fabrics with rougher surface texture. Following from a study focusing on the static interaction between the skin and fabrics, in the current experiment we 1) sought to identify the role of textile factors, such as surface texture and thickness as well as non-textile factors, i.e. local skin temperature changes and stickiness sensation on wetness perception under dynamic skin contact. Additionally, (2) we aimed to observe changes in fabric pleasantness and texture sensation between dry and wet state.

4.2 Method

4.2.1 Participants

Sixteen young (yrs. 22.4 ± 2.5) male (8) and female (8) participants, of Western European and North American origins, with no history of sensory related disorders and active at least 4-6 hours per week, volunteered to participate in this study. The test procedure and instruments were explained to each participant verbally and through a written information form. Following from this, participants gave written informed consent for participation. Due to the nature of the study, participants were not informed on the detailed aim of the study, experimental conditions, magnitude of the stimuli (amount of water applied) or type of fabric. The protocol and procedures involved were approved by Loughborough University Ethics Committee. The study was conducted within the confines of the World Medical Association Declaration of Helsinki for medical research using human participants.

4.2.2 Specimen

Eight knitted fabrics (120 x 100 mm) selected for different structure, fibre type, surface texture properties, thickness, and treatments were included in this experiment (Table 1).

The fabrics were grouped in 3 main clusters according to their thickness characteristics (Table 1): low (0.56-0.60 mm; L), medium (0.90-1.00 mm; M) and high (2.10 mm; H). The results of this study will primarily be applied for the design of base-layers sportswear, usually presenting low thickness characteristics, therefore four fabric samples were included in L and only two fabric samples were included in both M and H.

Within each thickness group the fabrics presented different surface texture (ST), measured as surface roughness (SMD) by the Kawabata Evaluation System (Kawabata 1980) (KES; higher ST corresponds to higher roughness) (Table 1). During the subjective assessments the face side of the experimental samples was tested only in wale direction; therefore the KES measurements were also performed in this direction and used for the estimation of ST.

The fabrics were coded according to thickness group (L = low thickness; M = medium thickness, H = high thickness), fibre type (CO = cotton; PM = polyester multi-channeled fibre cross-section; P = polyester) and ST (approximated surface texture, determined by rounding up to a whole number). For instance, MP2 stands for Medium thickness group, Polyester and ST of ~ 2. Table 1 reports specifications of the experimental fabric samples.

Table 1 Specifications of the experimental fabrics grouped according to low (L), medium (M) and high (H) thickness and presenting different surface texture (ST) measured as surface roughness (SMD) by the Kawabata Evaluation System. Water content was defined as equal water per volume of textile. The criterion for water content manipulation is reported in the 'Conditions' section.

Fabrics	Thickness Group	Thickness (mm)	Fibre type	Structure	ST (µm)	Mass ($g \cdot m^{-2}$)	Material description	Water content (µL)
	LOW							
LCO4		0.60	cotton	single jersey	3.7 ± 0.18	140	'fuzzy' texture	2400
LPM6		0.56	polyester	single jersey	5.9 ± 1.8	160	multi-chanelled fibre cross-section	2400
LP3		0.56	polyester	single jersey	2.6 ± 0.4	160	plain surface	2400
LP6		0.60	polyester	single jersey	6.4 ± 0.6	160	profiled surface	2400
	MEDIUM							
MP2		0.90	polyester	double jersey	1.9 ± 0.3	130	silicon treated 'silk-like surface'	3600
MP3		1.00	polyester	double jersey	2.7 ± 0.2	280	untreated 'standard surface'	4000
	HIGH							
HP4		2.10	polyester	double jersey	3.6 ± 1.4	330	'smooth' texture	8400
HP15		2.10	polyester	double jersey french terry	15.3 ± 1.7	330	'rough' texture	8400

LCO4: low thickness, cotton, approx. ST of 4; LPM6: low thickness, polyester with multi-channeled fiber cross-section, approx. ST of 6; LP3: low thickness, polyester, approx. ST of 3; LP6: low thickness, polyester, approx. ST of 6; MP2: medium thickness, polyester, approx. ST of 2; MP3: medium thickness, polyester, approx. ST of 3; HP4: high thickness, polyester, approx. ST of 4; HP15: high thickness, polyester, approx. ST of 15.

4.2.3 Experimental set-up

The experimental set up consisted of: a fabric sample, an adjustable chair where each participant was positioned and a fabric motion rig (Fig 1).

4.2.3.1 Fabric sample

To prevent water spreading across a fabric area larger than 120 x 100 mm, each long side of the experimental fabrics (120 x 100 mm) was fitted to a non-wicking material (200 x 120 mm). The two non-wicking materials together with the fabric, in between, formed the fabric sample.

4.2.3.2 Fabric motion rig

Each fabric sample (Fig 1) was placed in a custom-made linear motion rig. The sample was connected to a motor drive on one side and to a counterweight on the other side. The fabric sample could run over two rollers, creating a horizontal area of stimulation. Under this area, the right forearm of each participant was placed onto a height adjustable arm rest, such that the fabric touched the ventral forearm. The latter's setting was adjustable vertically to ensure equal pressure/ contact area in different size arms.

The ventral forearm was selected as body region of interest for practical reasons. In fact this body site allowed easy applications of the fabrics in relation to the design of the motion rig, yet maintaining the comfort status of the participants during the trial. Additionally, it has been indicated that the ventral forearm presents the same sensitivity to cold as the upper back (Parsons 2014), therefore the results can be compared with the existing literature (Sweeney and Branson 1990a; Raccuglia et al. 2016a).

A dividing wall was mounted onto the fabric motion rig, approximately half way between the forearm and the arm of each participant. With this setting the participants could not see the experimental textile samples before, during and after the application process; therefore any visual influence on the perceptual responses was prevented.

Each fabric sample was pulled bi-directionally across the skin at a velocity of 0.02 $m.s^{-1}$. Two fixed levels of pressure were applied: 127 Pa (LOW-P) and 236 Pa (HI-P). The order of this two pressure conditions was counterbalanced (the method to measure fabric-to-skin pressure is reported in the Conditions section). The range of travel of each fabric was of 5 cm per stroke, with a total of 8 strokes per fabric, 4 toward the medial forearm and 4 toward the lateral forearm.

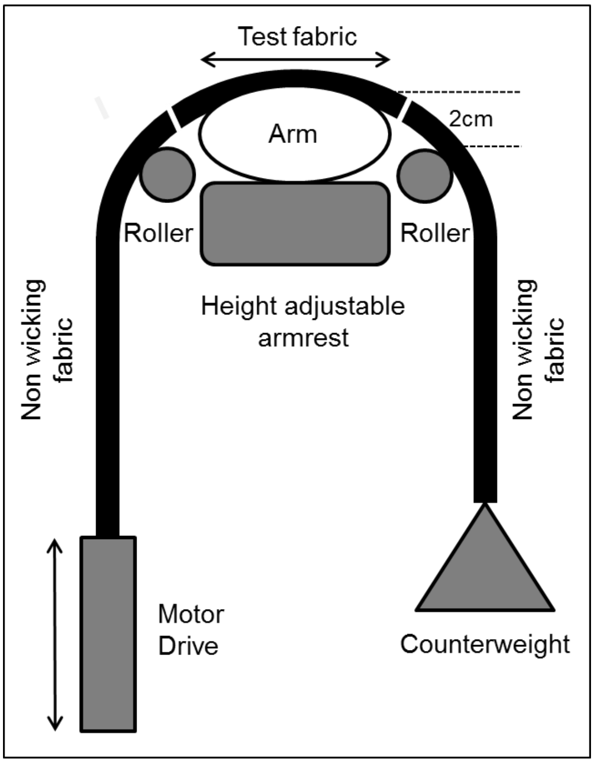

Figure 1 Schematic representation of the Fabric Motion Rig and experimental set up.

4.2.3.3 Adjusting chair and participants position

A chair was positioned at a standard distance from the fabric motion rig. After each participant settled on the chair, the investigator adjusted the position of the participant's right forearm on the armrest. The posterior margin of the olecranon was placed in line with the posterior edge of the armrest, the dorsal side of the forearm was located in contact with the armrest and the ventral side was left exposed, to allow the application of the samples. Because of individual forearm shape and size differences, to ensure standard level of contact between the sample and the ventral forearm, each forearm was maintained at a distance of 2 cm above the rollers of the motion rig. Additionally, the height of the chair was adjusted to achieve standard position of the forearm in respect to the arm (90° angle), which varied based on the individual height of the participants.

4.2.4 Conditions

The fabric samples were tested in wet (WET) and dry (DRY) state. In WET, the samples were all treated with an amount of water corresponding to 50% of their total absorption capacity, according to the wetting procedure described in Raccuglia et al. (2016). This amount was shown to deliver the same quantity of water per unit of volume of the different fabrics.

Water absorption capacity was determined according to the 'water absorption capacity test' described by (Tang et al. 2014a). For the test a fabric sample (100 x 100 mm) was put into a tank of water and 5 min was allowed for it to sink completely into water. Following from this, the fabric was taken out by tweezers and hung onto a rod vertically until there was no water dripping within a 30 seconds interval. The water gain was calculated according to:

$$Water\ absorbed\ (\mu L) = [wetF\ (g) - dryF\ (g)] * 1000\ \frac{\mu L}{g}$$

Where,

wetF, is the weight of the saturated fabric (g);

dryF, is the weight of the dry fabric (g).

The fabrics were wetted 30 min before the experimental trial, in accordance to the order (balanced) of application during the human sensorial assessment. Each fabric was positioned onto a plastic film and water was added by using a micropipette (SciQuip LTD, Newtown, UK) positioned at a fixed distance of 10 cm perpendicular to each sample and pointing at its centre. When the water was in equilibrium with the fabric, (specifically, when the water spread out uniformly across the sample; this took approximately 1 minute) each fabric was placed into a plastic bag which was securely sealed to prevent water evaporation. No water dripped from the samples inside the plastic bags during the storage period. Given that within each group the experimental samples had same thickness and same volume, the fabrics also presented the same relative to volume water content ($\mu L \cdot mm^{-3}$) and same, or almost the same, absolute water content ($\mu L \cdot mm^{-2}$) (Raccuglia et al. 2016) (Table 1).

The fabrics were also tested in the DRY condition to observe changes in texture and pleasantness sensation between WET and DRY. In the DRY condition no water was added to the fabric samples, which were in equilibrium regain with the environment (25 °C ambient temperature and 40% relative humidity). In DRY the pressure applied was of 127 Pa (same as LOW-P condition, see below).

To confirm the role of resultant fabric to skin pressure on wetness perception, as observed under static contact (Raccuglia et al. 2016), within the WET condition each fabric sample was tested at two pressure levels: low pressure of 127 Pa (LOW-P) and high pressure of 236 Pa (HIGH-P). The two pressure conditions were achieved using two different counterweights (200 g and 300 g), attached at one end of each experimental sample, and mounted on the fabric motion operator rig (Fig 1). Extensive pilot testing were conducted to define the two resultant skin pressures. Results indicated that a pressure of 127 Pa represented the lowest possible pressure applicable in order to ensure enough tension in each WET fabric sample during the pulling process across the skin and to avoid sticking. The HIGH-P of 236 Pa was chosen with the aim of achieving perceivable differences from the LOW-P condition without applying excessive mechanical stimulation. Given the significantly higher weight of the two counterweights compared to the individual wet weight of each fabric sample (4.05-12.00 g), the effect of fabric weight on resultant skin pressure was negligible. To measure the pressure resulting from the application of each fabric sample plus attached clamp and counterweight, a calibrated electronic weighing scale (PSK 360-3, Kern, UK), with a maximum load of 360 g and a precision of 0.001 g, was used. A cylinder with a forearm-like shape, made of hard foam, was placed on the measuring scale and each fabric, at both LOW-P and HIGH-P, was positioned on top of it. The two weight readings (g) were recorded and from these the two corresponding applied pressures (Pa), assuming a surface contact area of 10 x 10 cm, were calculated according to:

*Pressure applied (Pa) = Weight reading (kg) * 9.81 $m.s^{-2}$ / contact area (m^2).*

4.2.5 Study overview

Fabrics were assessed in one single experimental trial including 3 different conditions: DRY; WET LOW-P; WET HIGH-P. Replicates of the 8 experimental fabric samples were tested under the 3 different experimental conditions, therefore a total of 24 fabric samples were tested during the experimental trial. New fresh fabric samples were used for each participant. The fabrics were assessed using a quantitative sensory test, which consisted of placing, in counter balanced order, the 24 samples on the right ventral forearm of each participant. Participants reported their local texture sensation, wetness perception, stickiness sensation and pleasantness sensation on ordinal scales (see Measurements section). Prior to the experimental trial, participants were familiarised (~15 min) with the experimental protocol, procedures and instruments used in the present study. The experimental trial was conducted immediately after the familiarisation session. The experiment was performed in a climate controlled room, maintained at air temperature at 25.8 ± 0.2 °C, relative humidity 39 ± 0.7 % and air velocity < 0.05 m/s to ensure thermo-neutrality of the participants throughout the trial.

4.2.6 Experimental protocol

In the experimental trial participants entered the controlled climatic room and were positioned comfortably on the adjustable chair wearing standard T-shirt and shorts. Participants positioned their forearm on the armrest of the motion operator. A reference fabric sample (120 x 100 mm) was placed on the skin, with the long sides of the sample perpendicular to the longitudinal axis of the forearm and two lines next to these two sides were drawn on the forearm to identify the fabrics' area of application. The centre of the sample was positioned 2/3 above the distal margin of the carpus, the length of the ventral forearm was ~ 27 cm and it was measured from the distal margin of the carpus to the coronoid fossa. Participants were then instrumented with two thin skin temperature sensors (see Measurements section), in the skin area in contact with the fabric, and with temperature sensors across the body to measure body skin temperature. After this, participants rested for 20 min to allow time for skin temperature to stabilise. After the stabilisation period the investigator applied on the participants ventral forearm six reference fabrics, two for each ordinal scale, each corresponding to one of the two extreme points of texture, wetness and stickiness scale. The reference samples were chosen after extensive pilot studies. Specifically, a dry wool (very rough) and a dry silk (very smooth) materials were selected as references for texture sensation. Two samples of the same polyester fabric were used as 'extremely dry' (no water added) and as 'extremely wet' (50 % of the total saturation) references. For stickiness, a wet silk fabric (extremely sticky) and a cotton fabric (not-sticky), both presenting same thickness and water content, were chosen as references. The score of each reference fabric was reported by the investigator who also informed the participants that the intensity of the subsequent fabrics would not exceed the range of the two references for each scale. Following from this, each experimental fabric was applied on the participants' ventral forearm, moving for a period of 20 seconds. Participants were alerted by the investigator before the application of each fabric. At the end of the 20 seconds, participants were encouraged to verbally report their texture sensation, wetness perception, stickiness sensation and pleasantness for the stimulated body area, using the four ordinal scales. After 15 seconds of application, local skin temperature was recorded. After 20 seconds the fabric sample was removed and a dry cloth was placed onto the tested body area to avoid any chilly sensation, consequent to the evaporation of any remaining water on the skin. The tested skin area was then gently wiped with the cloth and dried by blowing warm air; this took approximately 2 min and allowed temperature and hydration state of the skin to return to baseline before the application of the following experimental fabric. Additionally, since the repeated application of dynamic wet stimuli can decrease thermal and tactile sensitivity, 2 min of rest, before the subsequent fabric application, allowed the recovery of the sensory system. The same protocol was repeated for each of the 24 fabrics. Each experiment (stabilisation, familiarisation and experimental trial) took approximately 2 hours and participants were instructed to ask for a rest whenever they felt uncomfortable.

4.2.7 Measurements

4.2.7.1 Surface texture

To characterise the surface texture of the experimental fabrics surface roughness (SMD) was measured using the Kawabata Evaluation System (KES). For the measurement a sensor contacts the surface of the fabric under a constant normal force. The sensor consists of a metallic rod connected, in its freed end, to a thin wire with a U shape. Surface roughness is calculated from electrical signal generated by the vertical displacement of the sensor contacting the fabric surface.

4.2.7.2 Skin temperature

Local skin temperature during the contact with each fabric was measured with two fine wire (0.025 mm diameter, time constant of 0.003 sec.) type T thermocouples (RS Components, Northants, UK). The thermocouple temperatures were monitored and recorded every second throughout the application of the stimulus via a Grant Squirrel SQ2010 data logger (Grant Instrument Ltd., Cambridge, UK). Local skin temperature was calculated from the mean of the two measured spots. Local skin temperature drop (Local T_{sk} Drop), resulting from the application of each wet fabric sample on the skin, was calculated according to:

Local T_{sk} Drop = PRE Local T_{sk} – POST Local T_{sk}

Where:

> *PRE Local T_{sk}* is the local skin temperature before the application of the wet fabric (baseline) in °C.
>
> *POST Local T_{sk}* is the resultant local skin temperature recorded at second 15 during the application period in °C.

Before testing, the thermocouples were calibrated by placing the measuring junction of each thermocouple in a circulating water bath whose temperature was monitored with a certified mercury thermometer.

To ensure thermo-neutrality, skin temperature of 5 body sites (check, abdomen, upper arm, lower back and back lower thigh) was measured throughout the experimental trial, with iButtons wireless temperature loggers (Maxim, San Jose, USA). From these five body sites, mean skin temperature, sampled every minute, was estimated according to the work of Houdas and Ring (1982).

4.2.7.3 Texture sensation

To assess perception of fabric texture, i.e. roughness and smoothness, an ordinal bipolar, balanced scale was developed (Fig 2: A). To prevent forced choice, the scale had a neutral (0) point in the middle, corresponding to 'Neither rough nor smooth'. From zero to 9 (progressive increase in texture), the scale presented different levels of roughness, whereas from 0 to -9 (progressive reduction in texture) different magnitude of smoothness were displayed. During the scoring process participants were instructed to first associate the texture of the sample with one of the two attributes, i.e. rough (positive side) or smooth (negative side) and then to report the magnitude of the specific attribute chosen.

4.2.7.4 Wetness perception

A 30 points unipolar ordinal scale (Fig 2: B) was adopted to assess fabric wetness perception. The scale ranged from 0 to 30, presenting descriptors at point 0, 5, 10, 15, 20, 25 and 30 (Raccuglia et al. 2016).

4.2.7.5 Stickiness sensation

Sensations of fabric stickiness were assessed using a unipolar ordinal scale, ranging from 0 (Not-sticky) to 12 (Extremely sticky) and intermediate descriptors at point 3, 6 and 9 (Fig 2: C).

4.2.7.6 Pleasantness sensation

A bipolar, balanced ordinal scale was developed to assess pleasantness sensation of the tested fabric samples (Fig 2: D). Same as the texture sensation scale, this scale presents an unforced choice at the middle point 0 (Neither pleasant nor unpleasant). Point -2, -4 and -6 were linked to the descriptors indicating progressive reduction in pleasantness, whereas points 2, 4 and 6 were linked to descriptors indicating progressive increase in pleasantness.

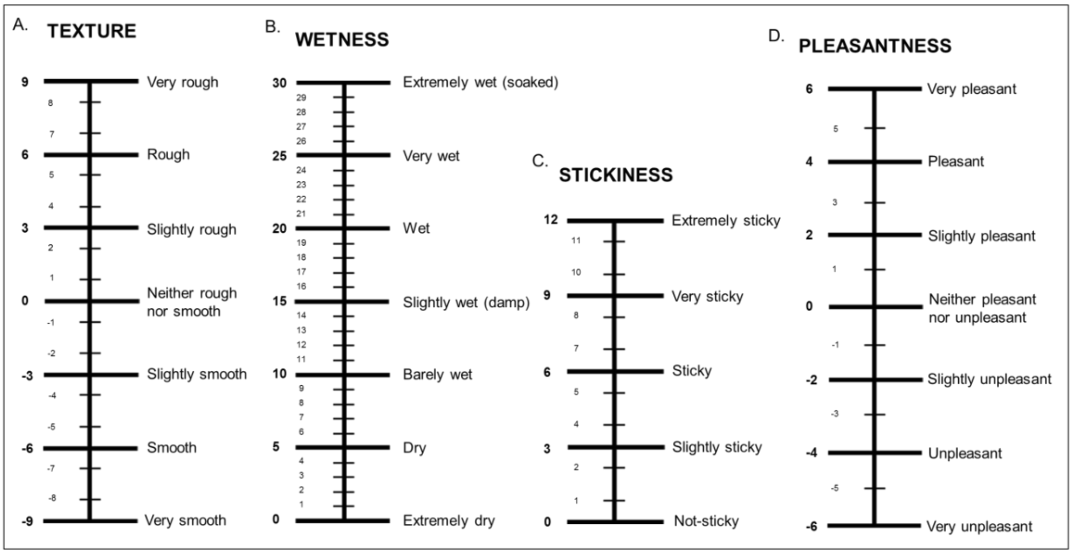

Figure 2A texture sensation scale; **2B** wetness perception scale; **2C** stickiness sensation scale; **2D** pleasantness sensation scale.

4.3 Statistics

The independent variables were: fabric thickness, fabric surface texture, skin pressure (HIGH-P versus LOW-P), wet state (DRY versus WET). Dependent variables were: Local T_{sk} Drop, mean T_{sk}, texture sensation, wetness perception, stickiness sensation and pleasantness.

Data were tested for normality of distribution and homogeneity of variance with Shapiro-Wilk and Levene's tests, respectively.

One way repeated measures ANOVA tests were conducted to assess whether mean T_{sk} was significantly different over time (T0-T55) and whether there were differences in local T_{sk} Drop (normalised data from baseline) between fabric samples tested under WET.

Texture, wetness, stickiness and pleasantness sensation data were measured through means of ordinal scales and also violated the assumption of normality of distribution, therefore for the statistical analysis non-parametric tests were conducted.

The main effect of fabric surface texture on wetness perception (WET) was tested by Wilcoxon Signed Rank test for M and H (2 levels of comparisons; MP2 and MP3for M, HP4 and HP15 H) and by Friedman analysis of variance test for LOW (4 levels of comparisons; LCO4, LPM6, LP3, LP6. Friedman test was also conducted to test the main effect of fabric surface texture on texture sensation. Where significant effect was found *post hoc* analysis was conducted by Wilcoxon Signed Rank Test.

Wilcoxon Signed Rank tests were conducted to test the main effect of resultant fabric to skin pressure on wetness perception (2 levels of comparison for each fabric, i.e. LOW-P versus HIGH-P) and the main effect of wet state on texture sensation and pleasantness sensation (2 levels of comparison for each fabric, i.e. DRY versus WET)

Regression analyses were performed to observe the relations within and between objective (i.e. Local T_{sk} Drop, fabric total water content, fabric thickness, surface texture) and subjective (i.e. wetness perception, stickiness sensation, texture sensation) variables, using data from group means. To choose the most suitable regression model, linear and second order polynomial analyses were performed for each subject. Individual r^2 values for linear and second order polynomial models were statistically compared using paired t-test. The regression model that explained the highest variance was then chosen for the analysis of group mean data.

In all analyses $p < 0.05$ was used to establish significant differences. Parametric data are reported as means ± standard deviation (SD). Data were analysed using the software IBM SPSS Statistics (version 22) (IBM, USA).

4.4 Results

4.4.1 Low pressure condition (LOW-P)

4.4.1.1 Wetness perception

In L (0.56-0.60 mm thickness) sample LPM6 was perceived significantly dryer ($p < 0.01$) than the other three samples (LCO4, LP3, LP6), whereas none of these three samples (LCO4, LP3, LP6) significantly differed from each other ($p > 0.05$) (Fig 3, panel B).

In M (0.9-1.00 mm thickness) MP2 was perceived significantly wetter ($p = 0.008$) than MP3 (Fig 3, panel B).

No significantly different wetness perception responses were found in H (2.1 mm thickness) between HP4 and HP15 ($p = 0.459$), (Fig 3, panel B).

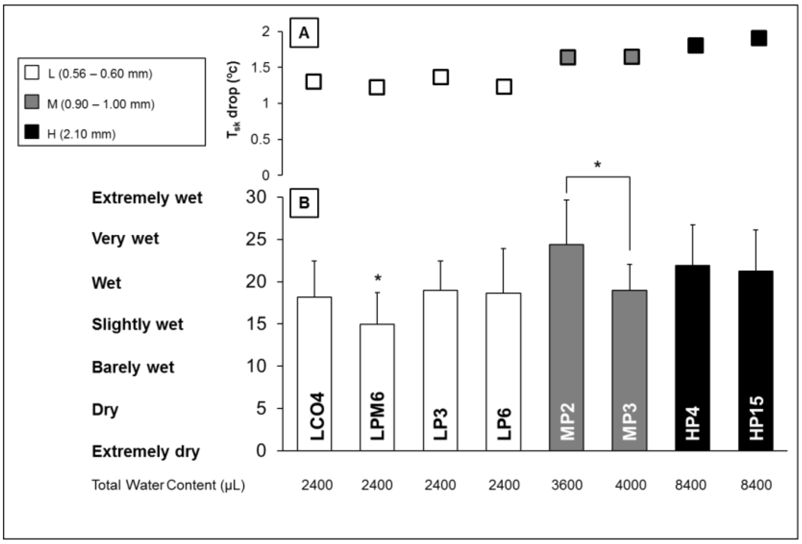

Figure 3 Panel A: average local T_{sk} (skin temperature) Drop from baseline (normalised data) in response to the dynamic application of each WET fabric sample in each thickness group: low (L), medium (M) and high (H). Panel B: * Significant differences ($p < 0.05$) in wetness perception responses between fabrics within L or M.

4.4.1.2 Mean and local skin temperature

Mean skin temperature (sampled every minute), averaged over time, was 33.9 ± 0.02 °C and did not significantly change ($p < 0.05$) throughout the trial.

Baseline local T_{sk} was 32.3 ± 0.2 °C and was not significantly different ($p < 0.05$) between each pre-application or condition (DRY, WET LOW-P, WET-HIGH-P).

Local T_{sk} Drop (data normalised from baseline), in response to the application of the wet fabrics, was not significantly different within each thickness group: $p = 0.85$ in L (0.56-0.60 mm thickness), $p = 0.89$ in M (0.9-1.0 mm thickness) and $p = 0.90$ in H (Fig 3, panel A).

A positive relation was observed between wetness perception and Local T_{sk} Drop ($r^2 = 0.48$, $p = 0.008$) (Fig 4).

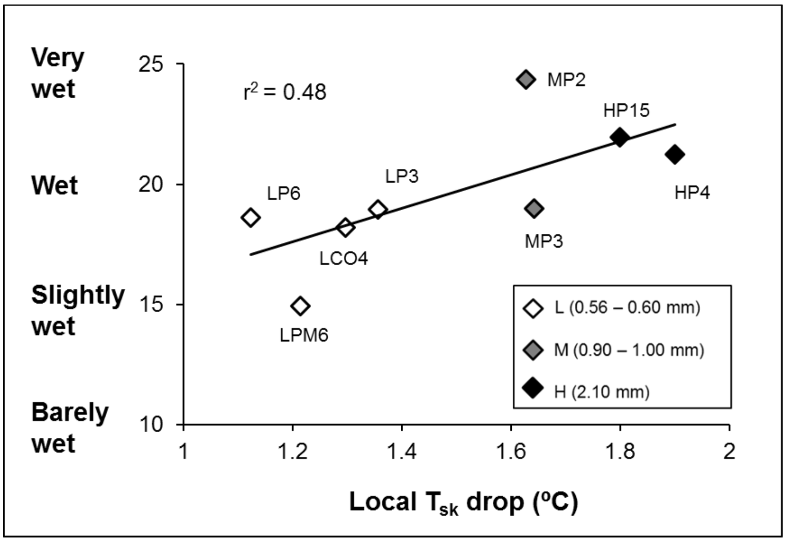

Figure 4 Relationship between wetness perception and local T_{sk} (skin temperature) drop in WET, LOW-P (low pressure) condition. Fabrics grouped according to L (low), M (medium) and high (H) thickness.

4.4.1.3 Relation between wetness perception and stickiness

A linear positive relation ($r^2 = 0.64$, $p = 0.007$) was observed between fabric wetness perception and stickiness sensation (Fig 5). Nevertheless, no relation was found between stickiness sensation and sample water content ($r^2 = 0.009$, $p = 0.82$).

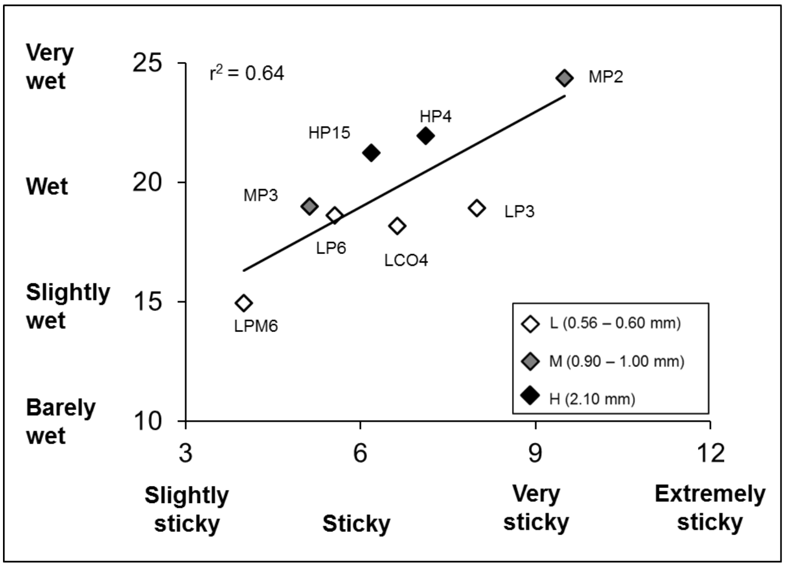

Figure 5 Relationship between wetness perception and stickiness sensation of the experimental fabrics tested in WET LOW-P (low pressure) condition. Fabrics grouped according to L (low), M (medium) and high (H) thickness.

4.4.1.4 Relation of stickiness sensation and wetness perception with texture sensation and surface texture (ST)

In WET no relationship was observed between stickiness sensation and texture sensation (r^2 = 0.087, p = 0.48) nor between stickiness sensation and surface texture (r^2 = 0.11, p = 0.42).

Wetness perception was not related to texture sensation (r^2 = 0.003, p = 0.96), neither to surface texture (r^2 = 0.001, p = 0.89).

4.4.1.5 Relation between wetness perception and fabric thickness

No significant relation was observed between wetness perception and fabric thickness (r^2 = 0.29, p = 0.166) (Fig 6). The lack of relation was mainly caused by fabric MP2 and LPM6, perceived as the driest and the wettest materials, respectively. In these two fabrics (LPM6 and MP2) the lowest and the highest wetness perception responses were not driven by their thickness or water content ($\mu L \cdot mm^{-3}$), but rather to their resultant stickiness sensation (MP2 most sticky, LPM6 least sticky; Fig 5).

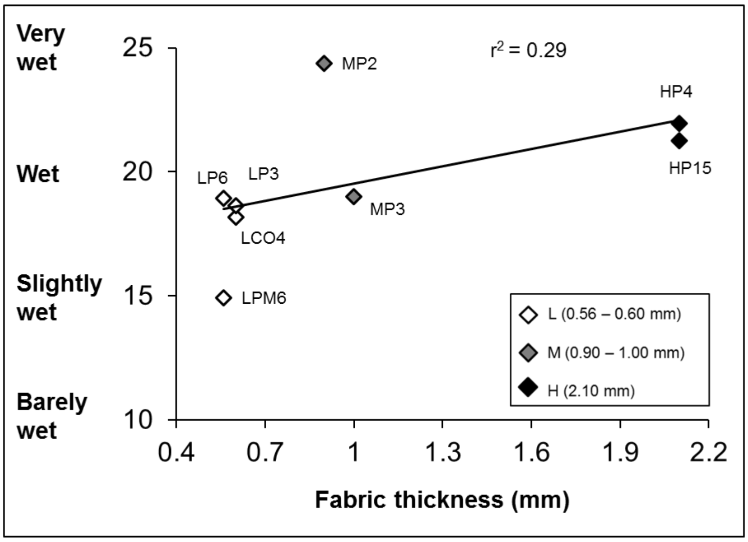

Figure 6 Relation between fabric wetness perception and fabric thickness in LOW-P (low pressure) condition. Fabrics grouped according to L (low), M (medium) and high (H) thickness.

4.4.1.6 Texture sensation and surface texture (ST)

In DRY a linear positive relation was observed between fabric texture sensation and surface texture (ST) ($r^2 = 0.79$, $p < 0.005$) (Fig 7a). The linear model was highly dominated by the roughest fabric HP15. When excluding this sample (HP15) from the model the relation appears less clear and only approaches significance ($r^2 = 0.55$, $p = 0.06$).

In WET the relation between texture sensation and surface texture (ST) was less clear compared to DRY and only approached significance ($r^2 = 0.48$, $p = 0.06$) (Fig 7b).

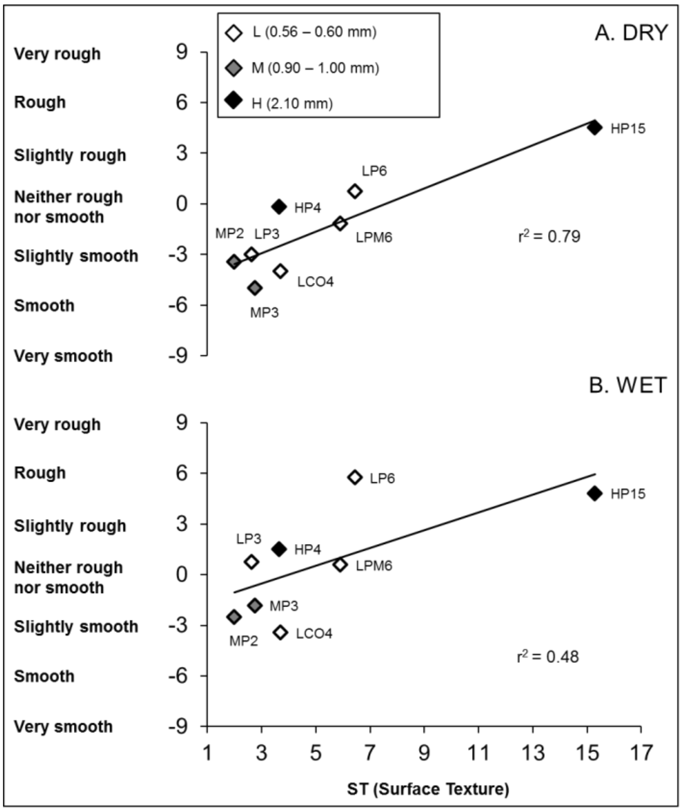

Figure 7A Relationship between fabric texture sensation (in DRY) and surface roughness (ST), **7B** relationship between fabric texture sensation assessed (in WET) and surface roughness (ST). Fabrics grouped according to L (low), M (medium) and high (H) thickness.

4.4.1.7 Wetness perception predictors

In order to define factors affecting fabric wetness perception under dynamic contact, stepwise regression analysis was conducted. For this analysis textile factors, such as fabric thickness and surface texture as well as non-textile factors such as Local T_{sk} Drop and stickiness sensation, were imputed as independent variables and wetness perception as dependent variable.

Fabric surface texture and/or texture sensation did not appear as relevant predictors. Wetness perception was described by stickiness sensation and Local T_{sk} Drop as the predicting variables (Table 2; MODEL 1), giving an explained variance of 89 %:

$$Wetness\ perception = 4.338 + Stickiness * 1.059 + Tsk\ drop\ * 5.583$$

Fabric stickiness sensation was the main predictor with a relatively larger Beta value at 0.64 (p = 0.008), while local T_{sk} drop was found to make a significant additional contribution to the predictive model (β = 0.53, p = 0.017).

Thickness alone did not predict wetness perception (Fig 6), mainly because of the latter's interaction with stickiness sensation. However, when replacing 'T_{sk} drop' with 'thickness' and including 'stickiness sensation' a similar prediction model of the one above is obtained ($r^2 = 0.86$, p = 0.003) (Table 2, Model 2; Fig 8).

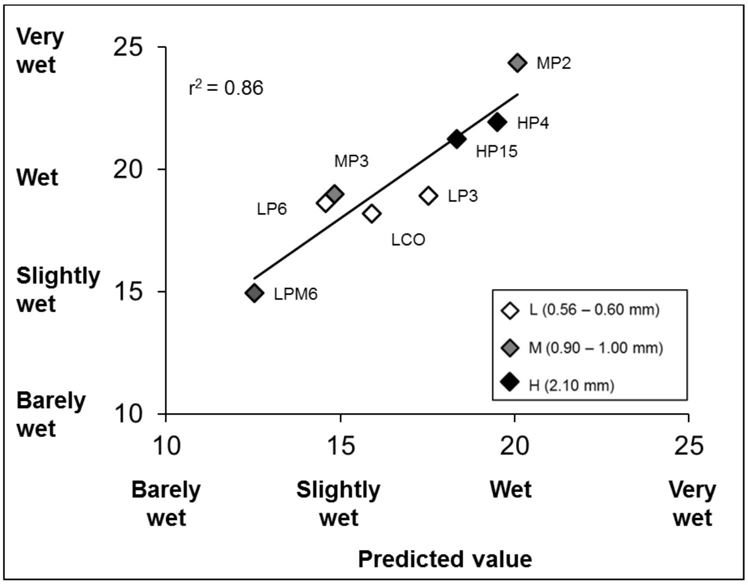

Figure 8 Representation of the prediction model of wetness perception (fabric stickiness sensation and fabric thickness as main predictors). Fabrics grouped according to L (low), M (medium) and high (H) thickness.

Table 2 Stepwise multiple regression analysis of wetness perception under LOW-P (low fabric to skin resultant pressure) condition.

		Unstandardized coefficient		Standardized coefficient				
Perceptual variables	Predictor variables	B	SD error	β	t	Sign.	F	r^2
MODEL 1 Wetness Perception	(Constant)	4.338	2.693		1.758	.006	22.051	.89
	Stickiness	1.059	.247	.642	4.290	.008		
	T_{sk} drop	5.583	.529	.529	3.529	.017		
MODEL 2 Wetness Perception	(Constant)	9.444	1.940		4.869	.005	15.322	.86
	Stickiness	1.247	.277	.756	4.493	.006		
	Thickness	1.985	.717	.466	2.770	.039		

4.4.2 High pressure condition (HIGH-P)

4.4.2.1 Wetness perception scores

Perception data from the high pressure condition (HIGH-P) were typically higher but showed similar patterns to those obtained in the low pressure condition (LOW-P).

In L (low thickness group) LPM6 was again significantly dryer compared to the other three fabrics ($p < 0.001$), LCO4, LP3 and LP6, whereas these three latter were not significantly different from each other ($p > 0.05$). In M (medium thickness group) MP2 was perceived significantly wetter than MP3 ($p < 0.05$) whereas in H (high thickness group) HP4 and HP15 were not significantly different ($p > 0.5$).

A linear relation was observed between WP and stickiness sensation ($r^2 = 0.79$, $p < 0.05$) whereas no correlation was observed between WP and thickness.

LOW-P and HIGH-P scores were compared to assess the role of resultant fabric to skin pressure on wetness perception. In HIGH-P samples were perceived significantly wetter ($p < 0.05$) compared to the LOW-P condition, apart from LPM6 and MP2 in which the differences were not significant ($p = 0.318$, $p = 0.975$, respectively) (Fig 9).

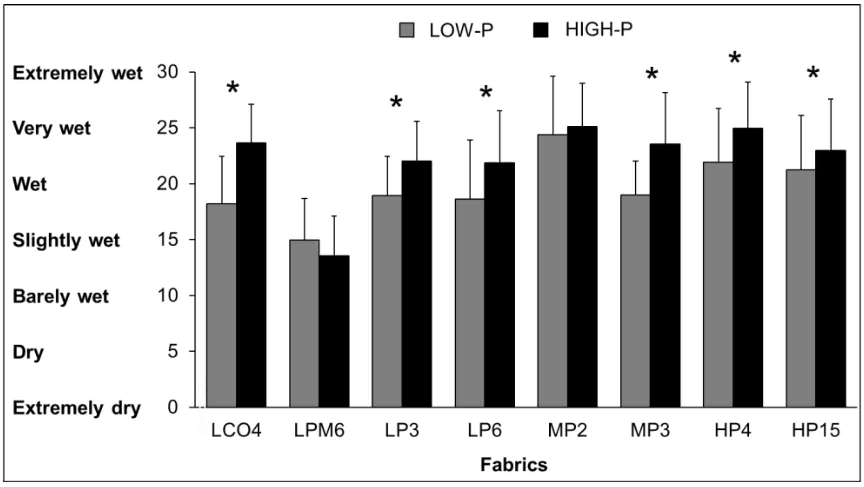

Figure 9 * Significant differences ($p < 0.05$) in fabric wetness perception between LOW-P (low pressure; grey bars) and HIGH-P (high pressure; black bars).

4.4.3 Texture and pleasantness sensation

Fabric pleasantness showed a significant relationship (second order polynomial fit) with texture sensation in both DRY (r^2 = 0.93, $p < 0.001$) and WET (r^2 = 0.89, $p < 0.001$), (Fig 10). Pleasantness was also significantly related (second order polynomial fit) with ST in DRY (r^2 = 0.75, $p < 0.005$) and WET (r^2 = 0.39, $p < 0.05$), although in WET the model presented a less predictive power.

Pleasantness sensation was significantly reduced in WET ($p < 0.05$) compared to DRY, apart from LPM6 and HP15 which did not present significant differences between the two conditions ($p = 0.53$, $p = 0.14$, respectively) .

Texture sensation increased in WET compared to DRY, however the increase was significant only in sample LP3 ($p = 0.05$), LP6 ($p = 0.001$) and MP3 ($p = 0.03$).

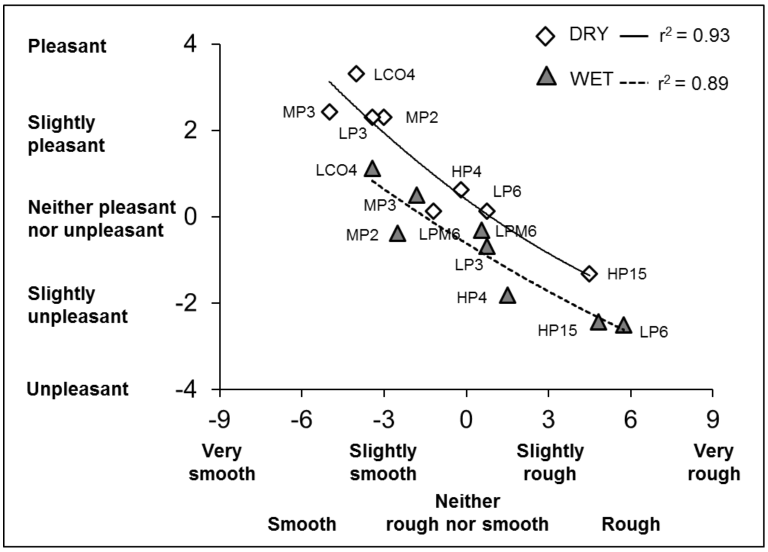

Figure 10 Relationship (second order polynomial fit) between fabric texture sensation and pleasantness sensation in DRY (diamonds symbols; solid curve) and WET (triangles symbols; dots curve) condition. Fabrics tested under LOW-P (low pressure) condition.

4.5 Discussion

The aim of the current study was to identify the textile properties triggering cutaneous tactile and thermal inputs underpinning wetness perception in dynamic skin contact. In order to correct for volume/thickness differences in fabric water content, the same relative to volume water amount ($\mu L \cdot mm^{-3}$) was applied, the latter corresponding to the 50% of the fabric's total saturation.

We hypothesised that, due to a greater number of contact points with the skin, fabrics with smoother surface texture will cause higher skin friction and/or displacement, sensed as higher stickiness and associated with greater wetness perception. Conversely to our research hypothesis, stickiness sensation and wetness perception did not show any correlation with the fabric texture property determined by the KES system and/or with texture sensation, and when conducting multiple regression analyses the latter were not identified as relevant predictors. Nevertheless, wetness perception was related with fabric stickiness sensation, therefore we could not totally reject our research hypothesis. In fact, we speculate that the lack of correlation was not due to a fundamental issue, but rather to a methodological issue, i.e. the Kawabata Evaluation system may not be an appropriate test method to predict stickiness sensation of wet fabrics.

With regards to wetness perception, the earlier observed relation to fabric thickness and skin cooling in static tests (triggering thermal responses; Raccuglia et al. 2016) was not observed here. However, when including stickiness sensation and therefore, correcting for the tactile responses, fabric thickness was shown to be a valid predictor and significantly contributed to the total variance (86 %) in fabric wetness perception under dynamic skin contact too. Similarly, when selecting local skin temperature drop (thermal cue) together with stickiness sensation (tactile cue) as independent variables, an even better model of fabric wetness perception is obtained (explaining 89 % of the total variance), indicating that the fabric thickness acts through its relation with the level of skin cooling based on the higher absolute water content of the thicker fabrics. In line with our previous work on static contact (Raccuglia et al. 2016a), also in dynamic contact under conditions of higher fabric-to-skin pressure (triggering mechanical stimuli), greater wetness perception responses were observed. The latter suggests that fabric weight can have an effect on wetness perception.

Finally, comparisons of texture sensation between wet and dry states indicated that under wet conditions fabrics felt more texturized compared to dry, causing reductions in pleasantness sensation.

4.5.1 Wetness perception and surface texture

Due to the critical impact of tactile sensitivity on wetness perception we hypothesised that fabric texture properties and/or sensation could affect wetness perception through changes in skin tactile responses, such as stickiness sensation. In particular, we expected the wet smoother surfaces to cause higher stickiness sensation; the latter likely due to the higher number of contact points between the skin and the fabric, also causing higher skin displacement compared to the rougher surfaces.

Two of the eight experimental fabrics (LPM6 and MP2) presented different wetness perception responses compared to those fabrics presenting same water content (Fig 3). However, these differences could not be attributed to the measured fabric texture propertiy, per se. For instance, in the low thickness group (L), LPM6 was perceived significantly dryer than LCO4, LP3 and LP6, and although LPM6 was rougher than LCO4 and LP3 it was not rougher than LP6 (Table 1). Additionally, LCO4, LP3 and LP6 presented the same wetness perception scores (Fig 3), despite differences in surface texture. Similarly, in the high thickness group (H), despite the surface texture of samples HP4 and HP15 was considerably different, 3.65 versus 15.3 respectively, no significant differences in wetness perception were observed (Fig 3). On the contrary in M (medium thickness group) wetness perception was significantly different between sample MP2 and MP3 (Fig 3) even though the difference in surface texture was quite small (1.9 versus 2.7, respectively).

The above-mentioned observations are validated by the lack of correlations between stickiness sensation and surface texture as well as between wetness sensation and surface texture, indicating that changes in stickiness sensation and related wetness cannot be attributed to the surface texture parameter (i.e. surface roughness), measured with the Kawabata Evaluation System. It could be argued that the ST of the samples was not different enough to show its influence on stickiness sensation (between 2.6 and 6.4, except for HP15 in which it was 15.3). However, despite these small differences in ST the participants could sense significant differences in texture across the fabrics, suggesting that that the Kawabata Evaluation System is not sensitive enough or as sensitive as humans.

The significant differences observed within the same thickness group, i.e. between fabrics presenting same absolute ($\mu L \cdot mm^{-2}$) and relative water content ($\mu L \cdot mm^{-3}$), suggest that certain surface and texture properties might still affect the mechanical interaction between the skin and the fabric under wet conditions. However, in order to asses this, other measures different from KES, or more suitable means able to characterise fabric surface properties are needed.

In L (low thickness group), LPM6 performed as the best fabric in terms of wetness perception, being perceived as drier than LCO4, LP3 and LP6. Fabric LPM6 is a polyester material in which the fibre cross-section consists of a series of closely spaced channels (either tetra- or hexa-channels) increasing the total surface area and facilitating the capillary action. As such, the theory is that moisture is wicked along the fibre surface and spread across a wider fabric surface area, enhancing evaporation. Hence, in LPM6 the faster evaporation rate should have resulted in a higher local skin temperature drop from baseline, however this was not the case (Fig 3, panel A). Therefore, it is possible that the fuzzy structure of LPM6 reduced the skin adhesiveness during the application process, causing lower stickiness sensation (Fig 5) and wetness perception. On the other hand, differences in fibre type between LCO4 (cotton) and LP6 or LP3 (polyester), did not determine changes in surface texture such as to affect stickiness sensation and related wetness perception. Similarly, the substantial difference in surface texture between LP3 and LP6, as well as between HP4 and HP15 did not influence stickiness sensation or wetness perception. These two pairs of fabrics had different knit structure, but the yarn type was identical. The latter suggests that changing the knit structure might not affect the mechanical interaction between the skin and the fabric; however the effect of yarn shape was not investigated. Finally, MP2 was perceived significantly wetter and stickier than MP3. Even in this case these differences could not be attributed to the texture parameters measured by the Kawabata Evaluation System, given that the difference in surface texture was minimal (1.9 in MP2 versus 2.7 in MP3). Nevertheless, it is likely that the silicon treatment applied to MP2 caused higher adhesiveness with the skin under wet conditions, resulting in higher stickiness sensation and wetness perception.

4.5.2 The role of tactile-sensitivity on fabric wetness perception

Unlike fabric surface texture, stickiness sensation was related to wetness perception. When the fabric and/or the skin is wet the higher adhesiveness (Nacht et al. 1981) increases the frictional force between the two surfaces (Nacht et al. 1981; Kenins 1994). In normal wear conditions the higher adhesiveness occurs in response to the increase in the size of the cells of the *stratum corneum,* when it is wet, which result in a higher number of contact points between the fabric and the skin (Gwosdow et al. 1986). This higher frictional force may cause greater skin displacement, sensed by the cutaneous mechanoreceptors as higher stickiness and perceived as greater wetness. Skin stickiness sensation was not related to fabric water content, likely because the experimental fabrics were tested under the same saturation level (50%). Additionally, given that the same pressure condition was applied, the individual weight of the fabric, pressing on the skin, did influence stickiness sensation. Based on this, the skin mechanical stimulation when in contact with a wet material might be affected by various factors and it seems not as straight forward to identify a single parameters triggering stickiness sensation.

The contribution of tactile-sensitivity to wetness perception is corroborated by the significantly different responses between high and low pressure conditions, also observed under static conditions (Raccuglia et al. 2016a). In fact, almost all of the experimental fabrics were perceived significantly wetter under higher compared to lower pressure conditions. Conversely, Filingeri et al. (2014b) observed a diminished wetness perception when increasing the contact pressure of the wet stimulus applied to the skin. In Filingeri's et al. study (2013) a significantly higher contact pressure was applied compared to the current study, (10000 Pa *versus* 260 Pa) suggesting that there might be a U-shape relationship between wetness perception and contact pressure. However, a contact pressure of 260 Pa seems more realistic for the current applications; therefore reducing the fabric-to-skin pressure is recommended for the design of clothing with reduced wetness perception.

The significant relation between wetness perception and stickiness sensation as well as the role of fabric-to-skin pressure, indicate that wetness perception can be manipulated by changing the tactile stimulation of the skin. In practice, using fabrics with reduced stickiness sensation features, together with the use of lightweight materials can help the clothing industry in designing garments with reduced moisture discomfort.

4.5.3 The role of thermo-sensitivity on fabric wetness perception

In line with the earlier results obtained in static applications (Raccuglia et al. 2016a), a significant relation was observed between wetness perception and local skin temperature drop. With the increase in fabric water content, the drop in local skin temperature also increases, the latter sensed as higher cooling and associated with greater wetness perception. Fabric water content is mainly influenced by fabric thickness (Raccuglia et al. 2016a). Because of the important relation between these two parameters, fabric thickness has been indicated as a critical factor affecting wetness perception under static fabric-to-skin contact (Raccuglia et al. 2016a).

In the current dynamic condition no significant relations were observed between wetness perception and fabric thickness. However, when examining the model, it is evident that the lack of relation was mainly caused by two fabrics: LPM6 and MP2. These two fabrics did not fit in the regression line, because of their significantly higher and lower stickiness sensation, respectively. The latter suggests that under dynamic skin contact fabric thickness can predict fabric wetness perception only when considered in combination with stickiness sensation. This was shown by the multiple regression analysis which indicated stickiness sensation and fabric thickness as valid predictor of wetness perception (r^2 = 0.86).

Because of the correlation between local skin temperature drop an thickness/water content (Fig 4) a similar prediction model is obtained when replacing the variable 'thickness' with 'local skin temperature drop'. Indeed, when using local skin temperature drop, instead of thickness, together with stickiness sensation as variables, a stronger prediction model is obtained (r^2 = 0.89). This means that local skin temperature drop is as better predictor than fabric thickness in dynamic conditions, pointing towards the temperature drop being the mechanism of action, and fabric thickness showing an effect due to its correlation with this, based on water content for evaporative cooling.

4.5.4 Pleasantness and texture sensation of dry and wet fabrics

Pleasantness and comfort are criteria commonly used by the users when selecting fabrics and clothing. Pleasantness was significantly reduced when fabric texture sensation increased (Fig 10). The significant relation between texture sensation and pleasantness indicates that fabric texture is an important parameter to consider in terms of clothing acceptability, in addition to wetness perception and thermal comfort. Interestingly, under wet state fabric texture sensation significantly increased compared to dry and resulted in a concomitant reduction in fabric pleasantness sensation. In line with this, Gwosdow et al. (1986b) indicated that fabrics feel more textured as skin wetness rose above 20%. Therefore, judgements of fabric texture and associated pleasantness can change in relation to the hydration state of the skin and/or fabric moisture content. As such, evaluations of fabric/clothing texture and related acceptability should be conducted under both dry and wet conditions.

Due to practical reasons and to prevent the effect of personal, environmental and clothing factors on the outcomes, in this study we studied comfort-related properties of fabrics only at the ventral forearm. We speculate that the current results could show a similar trend at different body regions; however it is unknown to what extent the outcomes will be different across the body. For instance, according to the mechanisms underlying skin wetness perception, body regional differences would likely depend on human sensorial factors, such as thermal and tactile sensitivity, as well as anatomical factors, i.e. hair distribution and differences between glabrous/non-glabrous skin. In terms of an overall garment, clothing factors, such as the air gap between the skin and the fabric as well as clothing fit (both influencing the level of fabric-to-skin contact) represent additional variables that would influence wetness perception responses across the body. Hence, future researches are necessary to understand how these initial results relate to an overall garment.

4.6 Conclusion

We studied textile and non-textile factors contributing to wetness perception of fabric treated with the same relative water content ($\mu l \cdot mm^{-3}$) and in dynamic skin contact conditions.

Local skin temperature drop/fabric thickness and stickiness sensation can predict wetness perception of fabrics in dynamic contact with the skin, whereas fabric surface texture measured by the Kawabata Evaluation System had no impact at all. The latter indicates that the Kawabata Evaluation system fails to predict stickiness sensation of wet fabrics, commonly assumed to be associated with fabric texture. Thus a different way to define fabric texture may be needed in order to represent this link (stickiness and texture).

Sensations of pleasantness are highly influenced by ST (surface texture measured by KES) and even more by the sensation of fabric texture (i.e. roughness and smoothness): as ST and the roughness of the fabric sensed on the skin increase, pleasantness sensation diminishes. Additionally, in wet conditions fabrics are sensed more texturized this resulting in a concomitant reduction in pleasantness sensation. Therefore, assessment of fabric pleasantness and acceptability in relation to fabric texture properties are recommended under both dry and wet conditions.

By identifying the textile and clothing parameters influencing skin wetness perception and related discomfort, this study provides fundamental knowledge for the design of clothing with reduced moisture discomfort features. Nevertheless, future researches are necessary to understand how this initial result related to an overall garment.

CHAPTER 5

Laboratory study 3

Anchoring biases affect repeated scores of thermal, moisture, tactile and comfort sensations in transient conditions

CHAPTER SUMMARY

In this study we addressed potential biases which can occur when sensorial scores of temperature, wetness and discomfort are repeatedly reported, in transient exercise conditions. We pointed out that, when repeatedly reported, previous sensorial scores can be set by the participants as reference values and the subsequent score may be given based on the previous point of reference, the latter phenomenon leading to a bias which we defined as ‘anchoring bias’. Indeed, the findings shown that subsequent sensorial scores are prone to anchoring biases and that the bias consisted in a systematically higher magnitude of sensation as compared to when reported a single time only. As such the study allowed recognition and mitigation of the identified bias which can improve the methodological rigour of research studies involving assessments of sensorial data in transient conditions.

5.1 Introduction

The direct study of human sensations and perceptions often requires the use of psychophysical scales. Psychophysical scales have been widely used to evaluate perceived exertion in physical exercise (Borg 1982), the thermal environment and thermal comfort (Backer 1948; Gagge et al. 1967; Auliciems 1981;Yang and Zhang 2008; de Dear 2011; Schweiker et al. 2017). In the context of clothing research and development, psychophysical scales have been largely used to assess thermal, moisture, haptic and comfort sensations while wearing clothing during rest and exercise conditions (Gagge et al. 1967; Fanger 1970; Hollies et al. 1979; Fanger 1986; Plante et al. 1995; Schneider et al. 1996; Fukazawa and Havenith 2009; Kaplan and Okur 2009; Jeon et al. 2011; Tang et al. 2014a; Raccuglia et al. 2016a; Raccuglia et al. 2017b). When using psychophysical scaling participants are asked to estimate the magnitude of a specific sensation by giving a number typically linked to a qualitative descriptor, i.e. slightly, very, or extremely (Li 2001; Cardello et al. 2003b). The International Standard, Ergonomics of the thermal environment - Assessment of the influence of the thermal environment using subjective judgement scales (ISO 10551:1995) contains a helpful guide on how to construct the scales used to measure human sensorial parameters, such as thermal sensation, thermal preference and thermal comfort. Whilst standardised guidelines (ISO 10551:1995) and important results (Gagge et al. 1967; Fanger 1970; McIntyre 1978; de Dear et al. 1997) have been provided for evaluations conducted in steady-state workplace conditions, they do not provide enough information regarding their repeated use over time, i.e. transient conditions, when sensations are repeatedly scored, at set intervals, over a certain period of time.

When sensorial scores are repeatedly reported in transient exercise conditions, the investigators need to decide between allowing participants to see their previous score (e.g. when scoring on sliders that remain static between scores) or preventing the use of their previous score for the following sensorial assessment (i.e. slider back to neutral point, or new fresh scale). In fact, in transient conditions, previous scores could be used by the participants as reference values. In this scenario, the subsequent score may be reported based on the previous point of reference, making the entire evaluation process relative to the past experienced sensation. The latter phenomenon can lead to a bias here defined as 'anchoring bias'. Anchoring biases can often result from the tendency of the participants to anchor the previously reported number (magnitude of sensation) rather than using the numbers in combination with the linked qualitative attribute of the sensation experienced. Furthermore, 'anchoring biases' are the consequence of individual preconceptions. For instance, participants could make the assumption that the magnitude of a specific sensation linearly increases with the increase of exercise duration, i.e. *'if 5 minutes ago my thermal sensation was '5', now that I have run for 5 minutes longer my thermal sensation must be higher (e.g '6').* In both scenarios where numbers (magnitude of sensation) are used as reference points, participants can lose the connection which the qualitative attribute of the experience sensation, this affecting the outcome of the research conducted. Therefore, to ensure scientific rigour when conducting studies involving consecutive sensorial assessments, it is important that the sensorial scores are not simply biased responses from the previous given score. To the knowledge of the author, it has not been demonstrated before whether, and to which extent, repeated sensorial assessments are prone to anchoring bias. As such, the aim of the current study was to assess whether there are systematic differences in sensorial scores reported at the same time point during 50 minute of running exercise, in different experimental conditions, but following a different assessment procedure i.e. subsequent scores (every 5 minutes) and single score at one time-point, independent of previous scores.

Specifically, since clothing strongly determines the thermal as well as comfort state of an individual (Havenith 1999; Havenith 2002; Raccuglia et al. 2016a; Raccuglia et al. 2017b), in this investigation we included assessments of thermal sensation, wetness perception, stickiness sensation and wear discomfort in relation to clothing. The current findings can be of high relevance when interpreting time courses of sensorial parameters, the onset of specific sensations, or when validating thermophysiological models.

5.2 Method

5.2.1 Participants

Ten young (26.9 ±3.4 yrs), healthy, recreationally active (strength and conditioning as well as aerobic exercises at least 4 times per week), male participants took part in this study. Their mean and standard deviation, body mass and height was, 73.5.0 ± 10.1 kg and 181.1 ± 8.1 cm, respectively. Participants were of Western European origin, to reduce any systematic error due to ethnicity-related differences in thermoregulatory responses, skin properties, and thermal as well as tactile sensitivity.

The experimental procedures were fully explained to the participants verbally and in writing, before obtaining written informed consent and completing a health screening questionnaire. All the experimental procedures involved were approved by the Loughborough University Ethical Committee. The study was conducted within the confines of the World Medical Association Declaration of Helsinki for medical research involving human participants.

5.2.2 Garment

The experimental garment included a short sleeved, regular fitted, 100% polyester T-shirt. A fresh pre-washed (ISO 6330:2012)T-Shirt was used for each participant and for each running trial. The T-Shirt specifications are presented in Table 1.

Table 1 Specifications of the experimental T-Shirt.

Fibre Content	Mass ($g \cdot m^{-2}$)	Thickness (mm)	R_{ct} ($m^2 \cdot °C/W$)	R_{ef} ($m^2 \cdot Pa/W$)	Air perm ($mm \cdot s^{-1}$)	Absorption ($g \cdot m^{-2}$)
100 % polyester	127	0.46	0.01	2.2	2088	368

R_{ct} = dry thermal resistance; R_{ef} = water vapour resistance, Air perm = air permeability, Absorption = total absorption capacity. Dry thermal resistance and water vapour resistance were measured according to BS EN ISO 11092:2014, air permeability was measured according to BS EN ISO 9137; total absorption capacity was measured according to the absorption capacity test adopted by Raccuglia et al.(2016), modified from Tang et al. (2014).

5.2.3 Trials

Participants performed one pre-test and three experimental trials on different days, separated by a minimum of 24 hours of rest. The pre-test involved anthropometric measurements of height, body mass (Mettler Toledo Kcc150, Mettler Toledo, Leicester, UK), and body dimensions to ensure adequate garment size used for the experimental trials. During the pre-test participants also performed a 20-min running test on a treadmill (h/p/cosmos mercury 4.0, h/p/cosmos Sport & Medical GmbH, Nussdorf-Traunstein, Germany). During this time the participants were asked to select the speed they could comfortably run for 1 hour. The selected speed (10.1 ± 1.0 km·h^{-1}) was then recorded and used for the following experimental trials.

Each experimental trial involved running on the treadmill at the fixed pre-selected speed for 50 min. In the first and the second experimental trial participants were asked to report, at specific time points, one single score of thermal sensation (TS), wetness perception (WP), stickiness sensation (SS) and wear discomfort (WD). By asking to report each sensation only at one single time point, it was attempted to prevent potential anchoring biases, therefore, the first and second experimental trial were defined as NO-ANCH1 and NO-ANCH2, respectively (Table 2). NOANCH1 and NOANCH2 only differed in the time point when the participants were asked to report the single subjective score of each investigated sensation (Table 2). In the third trial, participants were asked to score the same sensations at 5 min intervals, and due to potential anchoring biases, given by the repeated scores, this trial was defined as ANCH (Table 2).

Table 2 Schematic representation of the three experimental conditions

CONDITION	5 MIN	10 MIN	15 MIN	20 MIN	25 MIN	30 MIN	35 MIN	40 MIN	45 MIN	50 MIN
NO-ANCH1	-	-	TS	WD	SS	-	-	-	-	WP
NO-ANCH2	-	-	-	-	WP	TS	-	SS	-	WD
ANCH	TS-WD-SS-WP	TS-WD-SS-WP	TS-WD-SS-WP	TS-WD-SS-WP	TS-WD-SS-WP	TS-WD-SS-WP	TS-WD-SS-WP	TS-WD-SS-WP	TS-WD-SS-WP	TS-WD-SS-WP

NO-ANCH1 and NO- ANCH2 stand for no anchor effect trial 1 and no anchor effect trial 2, respectively. ANCH stands for ANCHOR EFFECT trial. TS = Thermal Sensation; WD = wear discomfort; SS = stickiness sensation; WP = wetness perception. In NO-ANCH1 and NO-ANCH2 participants were asked to report the score of TS, WD, SS and WP only once at a set time point, as reported in the table. In ANCH participants were asked to report the score of TS, WD, SS and WP at 5-min intervals.

5.2.4 Experimental protocol

In each trial (NO-ANCH1, NOANCH2 and ANCH) the same garment was worn. However, to blind the participant regarding the real aim of the study, they were told that they would wear, in the three separated experimental trials, garments treated with three different moisture transfer enhancing finishes and that the purpose of the investigation was to determine the best performing one. The sequence of the two NO-ANCH trials was counterbalanced, however, to prevent any between-condition anchoring bias the ANCH trial was always performed as last trial. During the pre-test participants were familiarised with the psychophysical scales used in the following experimental trials (Fig 1). During the experimental trials, each scale was displayed to the participants only when a specific score was required, in order to minimise memorisation of the previous score.

Participants were instructed to refrain from strenuous exercise, abstain from caffeine and alcohol consumption 24 hours before testing, and to keep a record of their food intake and replicate it the day before each visit. In order to maintain euhydration, they were also advised to consume 20 $mL{\cdot}kg^{-1}$ body weight of water during the two hours prior to testing. On arrival to the laboratory participants were instrumented with iButtons wireless temperature loggers (Maxim, San Jose, USA). From these five body sites, mean skin temperature (T_{sk}), sampled every minute, was estimated according to the work of Houdas and Ring (1982):

$$Mean\ T_{skin} = (cheek * 0.07) + (abdomen * 0.175) + (upper\ arm * 0.19) + (lower\ back * 0.175) + (back\ lower\ thigh * 0.39)$$

Participants also wore a wrist-based heart rate (HR) monitor (Polar A360, Polar Electro Oy, Professorintie 5, Kempele, Finland) and HR was recorded before and during the running trials at 1-min intervals. A wrist-based monitor, rather than a chest-based strap, was used since a chest strap would have interfered with sweat transfer from the skin to the T-shirt. Following from this, semi-nude (including underwear, iButtons, and HR monitor) body mass was recorded. Subsequently, participants were provided with standard running shorts and socks, worn with their personal running shoes, and were asked to use the same personal gear for the entire duration of the experiment. This period of preparation lasted approximately 20-min and allowed time for the stabilisation of HR and T_{sk}. Participants then moved to the climatic chamber, rested standing still on the treadmill and after 10-min baseline HR was recorded. They then donned the upper garment and the running trial started. In order to prevent dehydration, the participants were allowed to drink water *ad libitum* during the experiment, and liquid consumption was recorded. At the end of the run participants took off the worn T-shirt and hand it over to the experimenter for measurements of post-exercise garment mass. The amount of sweat absorbed by the upper garment ($SWEAT_{ABS}$) at the end of the running exercise was calculated as

$SWEAT_{ABS}$ ($g \cdot m^{-2}$) = $[(w_{wet} - w_{dry}]/SA$

Where;

w_{wet} garment wet weight (g)

w_{dry} garment dry weight (g)

SA garment surface area (m^2)

Participants took off shorts, socks and shoes, towelled their skin (this took ~ 2-min) and post-exercise semi-nude body mass was recorded. Sweat production was calculated based on the weight change of each participant (gross sweat loss, GSL), corrected for liquid intake, and reported in grams per body surface area ($g \cdot m^{-2}$), according to:

GSL ($g \cdot m^{-2}$) = $[w_{b1} - (w_{b2} - liquid)]/SA$

Where;

w_{b1} body mass at the start of the experiment (g)

The experiment was conducted in a climatic chamber maintained at 27.3 ± 0.2 ºC, 49.9 ± 5.6 % relative humidity and wind speed corresponding to 75 % of the individual running speed (9.5 ± 6.2 $m \cdot s^{-1}$).

5.2.5 Perceptual measurements

Wetness perception, stickiness sensation (SS), thermal sensation (TS), and wear discomfort (WD) were scored by the participants using psychophysical scales (Fig 1). Wetness perception was scored using a unipolar scale ranging from 0 (extremely dry) to 30 (extremely wet) (Raccuglia et al. 2016a; Raccuglia et al. 2017b). Stickiness sensation was scored using a 12-points unipolar scale (0 not -sticky, 12 extremely sticky) (Raccuglia et al. 2017b). Thermal sensation was scored using a bipolar scale ranging from -10 Cool to 15 Hot (Raccuglia et al. 2016a). Finally, the increase in wear discomfort was scored using a unipolar scale, ranging from 1 comfortable to 7 very uncomfortable (Fig 1).

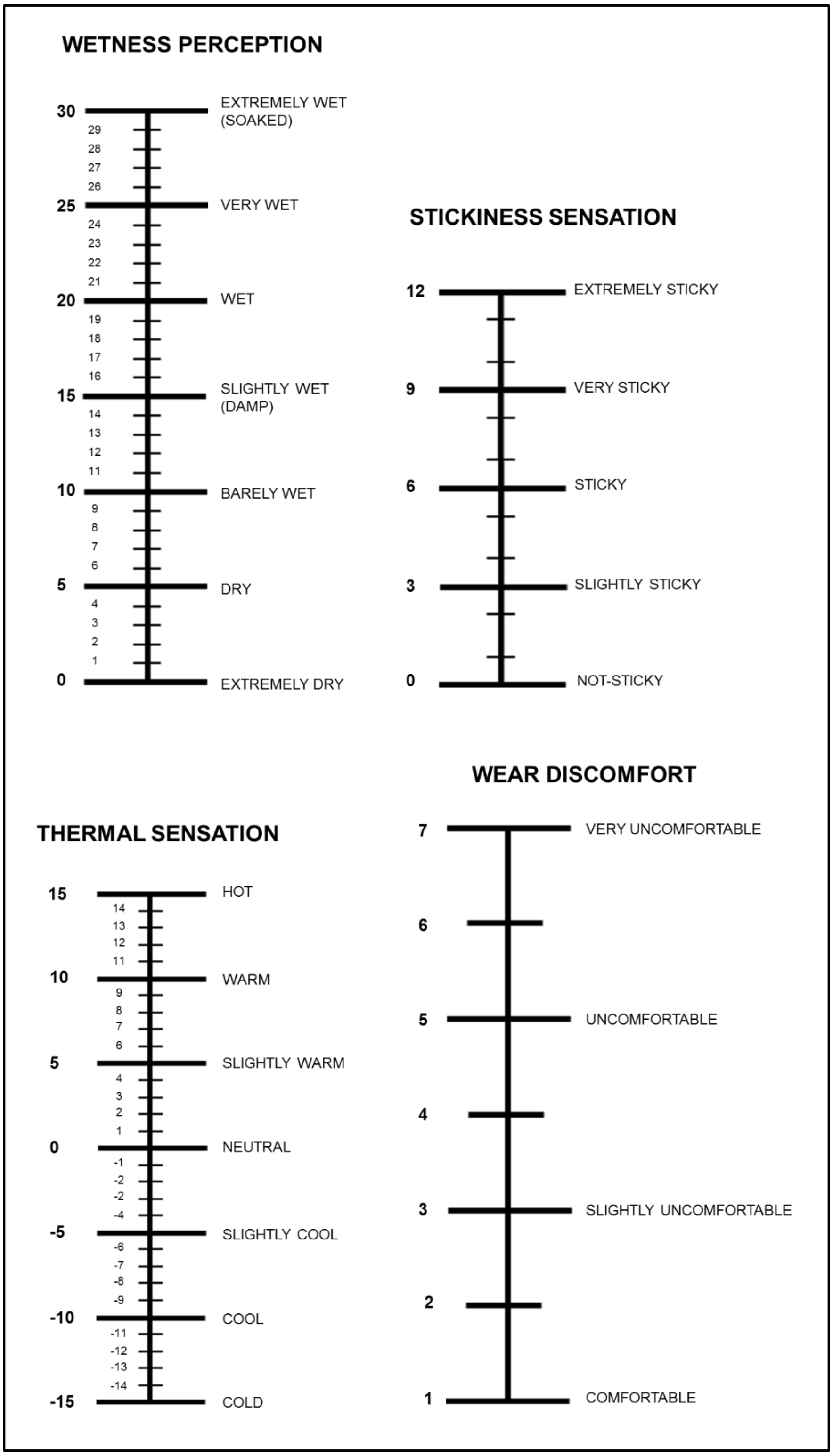

Figure 1 Perceptual scales. Participants scored each perceptual parameter by reporting verbally the selected number; each score was then recorded by the investigator.

5.3 Statistics

The dependent variables were: HR, T_{sk}, GSL (physiological) $SWEAT_{ABS}$, wetness perception, stickiness sensation, thermal sensation, and wear discomfort (sensorial).Data were tested for normality of distribution and homogeneity of variance with Shapiro-Wilk and Levene's tests, respectively. One-way repeated measures ANOVA tests were performed to assess differences in HR, $T_{sk,}$ GSL and $SWEAT_{ABS}$ between the trials (NO-ANCH1, NO-ANCH2 and ANCH). Non-parametric Wilcoxon Signed Rank test were conducted to assess differences in wetness perception, stickiness sensation and wear comfort between the trials (NO-ANCH1, NO-ANCH2 and ANCH) at the selected time points (Table2). In all analyses $p < 0.05$ was used to establish significant differences. Data are reported as mean ± standard deviation. Statistical analysis was performed using the software IBM SPSS Statistics version 23 (IBM, Chicago, USA).

5.4 Results

5.4.1 Physiological measurements

There were no significant differences in the amount of total sweat produced (GSL) ($p = 0.54$), hear rate (HR) ($p = 0.48$) and amount of sweat absorbed by the garment ($SWEAT_{ABS}$) ($p = 0.76$) between the three experimental trials (NO-ANCH1, NO-ANCH2, ANCH) (Table 3). Mean T_{sk}, measured at 1-min interval and sampled over 5-min intervals during the whole duration of the run (Fig 2), was not significantly different between the three trials (NO-ANCH1, NO-ANCH2 and ANCH) at any time point ($p > 0.05$). Therefore, the three trials provided same thermal load and thermoregulatory responses for each participant which resulted in same level of garment physical wetness. Based on this, it can be inferred that potential systematic differences in sensorial scores can only be due to the methodology in which the participants were asked to report the sensorial scores, i.e. at 5-min intervals (ANCH) or at one single time point (ANCH1 and ANCH2).

Table 3 Physiological responses across the three experimental trials.

CONDITION	GSL ($g \cdot m^{-2}$)	$SWEAT_{ABS}$ ($g \cdot m^{-2}$)	HR (bmp)
NO-ANCH1	519.6 ± 89.1	94.0 ± 56.5	152 ± 11
NO-ANCH2	514.8 ± 94.1	98.3 ± 66.1	156 ± 9
ANCH	514.7 ± 96.0	96.8 ± 62.2	154 ± 10

NO-ANCH21 and NO- ANCH2 stand for no past anchoring effect trial 1 and no anchor effect trial 2, respectively. ANCH stands for past anchoring effect trial. GSL = gross sweat loss; $SWEAT_{ABS}$ = amount of sweat absorbed by the upper garment at the end of the running exercise; HR = heart rate at the end of the run (at 50-min). Data are presented as mean ± standard deviation.

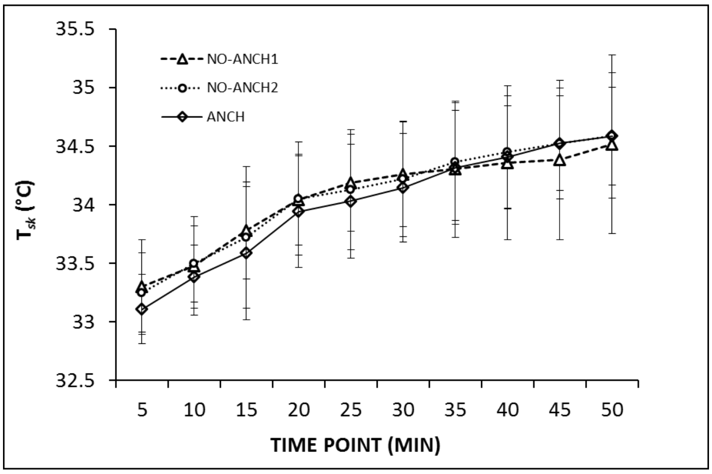

Figure 2 Time course of mean skin temperature (T_{sk}) recorded at 1-min interval and sampled every 5-min in the NO-ANCH 1 and NO-ANCH2 trials (no past anchoring effect) as well as in the ANCH (past anchoring effect) trial.

5.4.2 Sensorial scores

For clarity, the duration of the running trials is divided in two parts. The first part of the run ranges from 5 min to 25 min, the second one from 25 min to 50 min. The results show that the scores reported at 5-min intervals in ANCH were always higher than the single time-point scores obtained from NO-ANCH1 and NO-ANCH2 (Figure 3, Table 4).

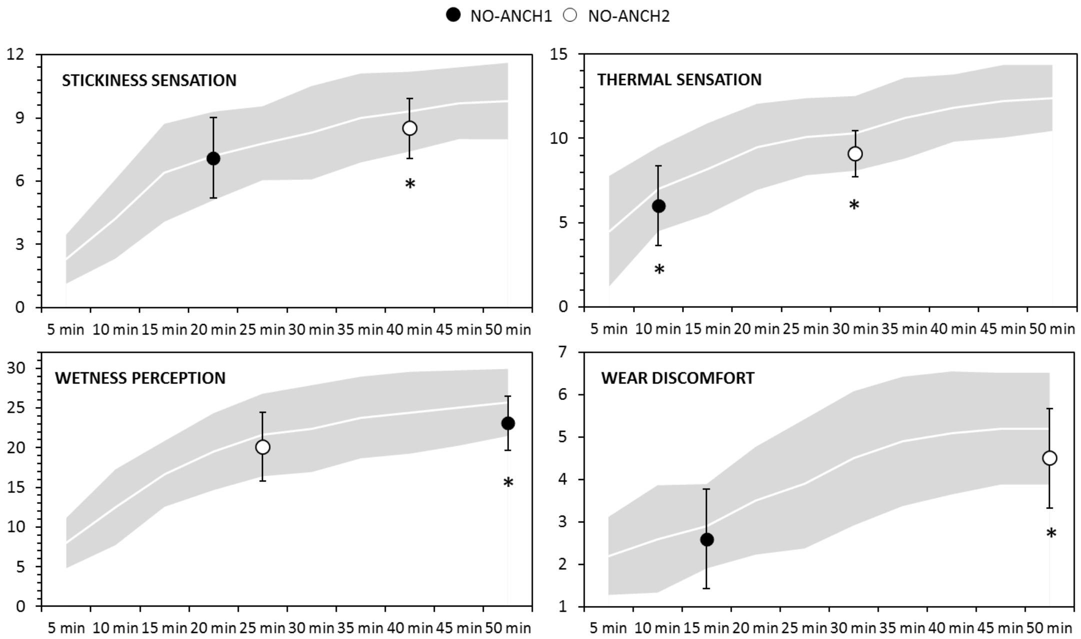

Figure 3 Reported perceptual scores of Stickiness Sensation, Thermal Sensation, Wetness Perception and Wear Discomfort. The solid line represents the perceptual scores reported at 5-min intervals in the ANCH trial, and the grey area indicates the corresponding standard deviation. The black and white circles represent means of the single time point sensorial scores reported in NO-ANCH1 and NO-ANCH 2 trial, respectively. *significant differences ($p < 0.05$) between NO-ANCH1 and ANCH as well as between NO-ANCH2 and ANCH at specific time points.

In the first part of the running trial (5 min to 25 min), only sensorial scores of thermal sensation were significantly higher ($p = 0.017$, $z = -2.43$) in ANCH, compared to NO-ANCH1 (Fig 2, Table 4), whereas scores of stickiness sensation, wetness perception and wear discomfort did not reach significance ($p = 0.77$, $z = -0.33$ stickiness; $p = 0.06$, $z = -1.89$ wetness; $p = 0.2$, $z = -1.34$ discomfort). In the second part of the running trial (25 min to 50 min), all the investigated sensations (wetness perception, thermal sensation, stickiness sensation and wear discomfort) were significantly higher ($p < 0.05$) in the ANCH trial compared to the NO-ANCH1 and NO-ANCH2 ($p = 0.02$, $z = -2.36$ thermal; $p = 0.03$, $z = -2.13$ stickiness; $p = 0.01$, $z = 2.49$ wetness; $p = 0.02$, $z = 2.33$ discomfort) (Fig 3, Table 4).

Table 4 Sensorial scores in ANCH, NO-ANCH1 and NOANCH2, at the selected time points (Table 2)

Sensorial score	ANCH	NO-ANCH1	ANCH	NO-ANCH2
Wetness Perception	25.7 ± 4.2*	23.1 ± 3.4	22.2 ± 4.2	20.1 ± 4.3
Thermal Sensation	7 ± 2.5*	6 ± 2.3	10.3 ± 2.2*	9.1 ± 1.4
Stickiness Sensation	7.2 ± 2.1	7.1 ± 1.9	9.3 ± 1.9*	8.5 ± 1.4
Wear Discomfort	2.9 ± 1.0	2.6 ± 1.2	5.2 ± 1.3*	4.5 ± 1.8

NO-ANCH 1 and NO-ANCH2 trials = no anchoring effect, trial 1 and trial 2, respectively. ANCH = anchoring effect trial. * Significant differences ($p < 0.05$) between ANCH and NO-ANCH1 and between ANCH and NO-ANCH2.

5.5 Discussion

The focus of this study was to assess whether, and to which extent, 'anchoring biases' occur when the magnitude of specific sensations is repeatedly reported in exercise. Our main finding was that scores of thermal, stickiness, wetness and discomfort sensation are significantly higher when subsequently reported at set intervals (every 5 min), as compared to single time-point scores. These findings show that subsequent sensorial scores are prone to anchoring biases, and that the bias consists in a systematically higher estimated magnitude of a particular sensation as compared to when reported a single time only.

Psychophysical scaling and past anchoring bias

Psychophysical scaling gathers direct information regarding the subjective experience that a person has in a specific environment. Sensorial data obtained from psychophysical scales can be considered as self-reported data. The common assumptions made with self-reported sensorial data is that the data represent an accurate, unbiased reflection of what is being measured (Dodd-McCue and Tartaglia 2010). However, the validity of subjective data (obtained using psychophysical scales) is often questioned (ISO 10551:1995). Particularly, self-reported data can introduce biases, mainly originated from the subjective nature of the human participants. Biases can affect the quality of the measurement, causing inaccuracy or lack of precision of the research. Participants can be inaccurate or cause biased responses for numerous reasons (Aaker et al. 2004). For instance, participants may want to be consistent in their responses, rather than focusing on the question asked. In other cases, participants might be concerned on how their responses can affect the opinion that others (investigator) can have of them (Mick 1996). In the literature, several biases related to self-reported data are examined (Krosnick 1999; Polit and Beck 2004; Dodd-McCue and Tartaglia 2010). However, there are not information available regarding potential biases occurring when sensorial data are repeatedly reported over time in exercise; the latter being the focus of the current study. Specifically, here we considered over-time assessments of temperature, stickiness, wetness and discomfort, in relation to clothing during exercise. We hypothesised that, when sensorial data are repeatedly reported over time, the previous provided score might serve as reference for determining the subsequent response. This phenomenon might sound similar to the so-called 'halo effect' (Polit and Beck 2004), in which the individual assessment of a certain object triggers the pattern of the following response. However, in the current study we hypothesised that the previous reported data is set by the participants as reference to intentionally report a subsequent response different from the one previously provided. This could be simply based on the assumption that over time the magnitude of a certain sensation must change, as exercise time/intensity increases. To test this hypothesis, in the current investigation sensations of temperature, wetness, stickiness and wear discomfort were measured at set single time-points, over 50-min of running exercise, and compared to the response provided (in a separated trial) at the same time point, but as part of subsequent measurements, i.e. every 5 minutes. In line with our hypothesis, repeated measurements significantly differed from single time-point measurements. Specifically, systematically higher scores were identified when provided multiple times as compared to the single-time scores (Fig 3). Differences in sensorial responses between ANCH and NO-ANCH condition were manly affected by the scoring procedure adopted (i.e. repeated versus single time scores). In fact, physiological parameters of mean skin temperature, heart rate and gross sweat loss, were not significantly different between the experimental trials. Core temperature, usually measured rectally or via an oesophageal probes, was not measured to avoid potential discomfort which could interfere with the sensorial responses of temperature, wetness, stickiness and wear discomfort.

According to these findings, here we propose that when reported in a repeated evaluation process (at set intervals, over time, in exercise), the previous score is set as reference to intentionally provide a greater subsequent score. This can be affected by the tendency of the participants to anchor to previous numbers rather than using the qualitative attribute as reference. In fact, when using numbers rather than the attributes, participants can lose the link with the actual magnitude of the sensation experience. Furthermore, anchoring biases can occur as result of a biased individual’s preconception that the progression of exercise time/intensity is accompanied by concomitant increases of the magnitude of a specific sensation, even if a greater sensation is not necessarily perceived. In cognitive psychology, this phenomenon can be recognised as schema. Schemas are stored in long-term memory and include knowledge about events and consequence of events (scripts) (Eysenck and Keane 2010). Schemas allow us to form expectations, as in this case, as exercise progresses participants expect to have higher body temperature and sweating responses, which can influence the magnitude of the related sensation reported.

Anchoring biases represent limiting factors in studies aiming to identify critical threshold values, i.e. onset of fatigue or discomfort, and associated sensations of temperature and wetness. However, this kind of bias might not represent an issue if the aim of the research is to simply discriminate between two or more items (i.e. garments). In fact, in this type of research, it is important to assess the discriminatory power between items but the magnitude of the score per se is not relevant. However, anchoring biases can lead to a ‘ceiling effect’. In exercise, this can occur when the score becomes progressively higher over time, to the point where the maximum value on the scales is prematurely reached before the end of the evaluation process, i.e. when assessing perceived exertion (Borg 1982) induced by different exercise protocols/stimulations. As such, once the highest value of a particular scale is achieved, discriminations between items cannot be made. On the contrary, based on the current findings, in other settings having a previous score value as reference can help to make more accurate judgments, meaning that the tendency to anchor to the previous score not always lead to a bias. This can occur when participants have to make estimations regarding the magnitude of absolute, continuous values, i.e. estimations of time progression, for instance.

Recognition and mitigation

Self-reported data are one of the most effective and appropriate way to gather information regarding the magnitude of specific sensations (Dodd-McCue and Tartaglia 2010), in our case, temperature, wetness, tactile and discomfort, while wearing clothing during exercise. When conducting research involving sensorial subjective data, it is common to pay attention to sample size, research design and statistical analysis, to improve methodological rigour. An additional factor needs to be considered by the researcher and this is the recognition of the potential bias, which is intrinsic of sensorial self-reported data. In fact, while it seems unrealistic to completely prevent and avoid biases, it is possible to address some of them before and during the data collection, to obtain a more precise interpretation of the study results. Particularly, in this study after recognition of the anchoring bias, the magnitude of the bias was quantified (Fig 3, Table 4).

Mitigation of the bias is the second step which should be considered by the researcher. It is crucial to identify the factors that can make the subjective sensorial response prone to bias. In the current study, to mitigate the past anchoring bias, specific strategies were adopted. For instance, while in some research set-ups it is common to show to the participants the scales during the entire duration of the experimental trial, in this study each scale was displayed only when a specific sensorial score was required. As such, memorisation and habituation to the scales, which could contribute to anchoring biases, were prevented. Anecdotally, in the trial requiring repeated sensorial scores, some participants asked the investigator, to remind them their previously reported score, before giving the next one. This event clearly demonstrates that participants tend to 'anchor' to the previous score and to set it as reference for the following one. Therefore, an additional strategy adopted to mitigate the bias was to negate reminders of the previous score and encourage the participant to focus and keep the connection with the sensation experience at that specific time point, using numbers as well as qualitative sensory attributes. Finally, another strategy which could further mitigate anchoring biases consists of reducing the frequency in which sensorial scores are asked to be reported. A longer interval between two consecutive scores could attenuated memorisation, and in this way participants become less prone to relate the following score to the previous given one.

5.6 Conclusion

The aim of the current study was to investigate the use of psychophysical scales in transient conditions, when the magnitude of a sensation is repeatedly scored, at set intervals, over a certain period of exercise time. Repeated sensorial scores were compared with single time point score, assessed in the same exercise and environmental conditions. This investigation demonstrated that repeated scores of thermal sensation, wetness perception, stickiness sensation and wear discomfort, in relation to clothing, during exercise, are significantly higher than single time point scores. This confirms our hypothesis that when repeatedly reported in transient exercise conditions, sensorial scores are prone to anchoring biases. In particular, due to the tendency to anchor to the previous number, rather than the sensorial descriptor, and to a bias preconception that sensations are linearly related to exercise progression, participants tend to intentionally give a score which is systematically higher than a score given in the same situation but a single time only. Although in the current study the sensation investigated where related to clothing, we speculate that same past anchoring biases can occur when assessing other subjects, e.g. thermal environment, vision, noises, fatigue or exercise. While complete abolishment of anchoring biases seems unrealistic, we recognised and quantified the bias which is important for the interpretation of future study's results. Finally, we provided strategies to mitigate the bias, in order to improve the rigour of research involving sensorial self-reported data.

CHAPTER 6

Laboratory study 4

The effect of garment contact area, absolute sweat content and sweat saturation percentage on moisture-related sensations during physical exercise

Publications based on this chapter:

Raccuglia M, Sales B, Heyde C, Hodder S, Havenith G. (2017) Clothing comfort during physical exercise – Determining the Critical factors. *Journal of Applied Ergonomics.*

CHAPTER SUMMARY

In Study 2, the individual impact of fabric contact area on wetness and stickiness sensation has been studied in a skin regional experiment at rest. Results demonstrated that lower fabric contact area causes diminished moisture-related sensations, i.e. wetness and stickiness. Following on from this, the current study investigated the combined effect of fabric contact area, fabric absolute sweat content and fabric moisture saturation percentage on wetness and stickiness sensations, during exercise at 27ºC and 50% relative humidity. Moreover, factors causing wear (dis)comfort during exercise were identified. Reductions in fabric contact area caused higher fabric moisture saturation percentage. Higher fabric saturation percentage induced greater stickiness sensation, despite lower fabric contact area and absolute sweat content (typically associated with lower stickiness). Wetness perception did not change between fabrics with different saturation percentages, contact areas and sweat contents. Texture and stickiness sensation explained 30% (at baseline) and ~50% (during exercise) of the variance in wear discomfort, respectively. In conclusion, fabric saturation percentage mainly affects stickiness sensation of wet fabrics, overruling the impact of fabric contact area and absolute sweat content. In a warm environment, the cooling sensations arising from sweat evaporation seems not to be sufficient to perceive differences in wetness between fabrics, thus stickiness seems a more impactful parameter. No overall model of wear discomfort across all data could be developed, likely due to the complex interactions between the relevant parameters and the time-dependency of the relationships. Therefore, models for different time points were produced, with texture and stickiness sensations being the best predictors of wear discomfort at baseline and during exercise, respectively. This suggests that the factors determining clothing (dis)comfort are dynamics and alter importance during exercise activity.

6.1 Introduction

Comfort is often considered in relation to a single factor causing discomfort, be it environmental, physical, physiological or perceptual (Slater 1986; Kaplan and Okur 2009; Kamalha et al. 2013; Parsons 2014). However, in a real life situation it is rare that only one single factor entirely influences how comfortable an individual feels. Clothing, for instance, constantly interacting with the human body, is responsible for wear discomfort. The clothing system can be considered as a combination of various interacting components that ultimately affect overall clothing functionality and wear comfort sensation. The clothing components can be grouped into two main clusters. The first one is represented by textile factors including the basic yarns and fibres used to knit or weave the fabric, the fabric itself, characterised by different physical parameters (thickness, mass, yarn count, stich density), structures, surfaces and geometries as well as finishes and treatments. The second group includes clothing factors, such as clothing design, fit and openings. Moreover, environmental and individual (including anatomical, physiological, and sensorial) factors interact with the clothing system (Hollies et al. 1979) leading to a highly complex environment- human- clothing system. One of the factors considered as the most crucial in causing wear discomfort during physical activity is the presence of wetness at the skin-clothing interface (Fukazawa and Havenith 2009; Gerrett et al. 2013). The multisensory modality of skin wetness perception contributes to the complexity in studying discomfort during wear. Due to the absence of defined cutaneous sensors (Clark and Edholm 1985) skin wetness is perceived in the central nervous system through the integration of other cutaneous stimulations (Bentley 1900; Niedermann and Rossi 2012; Filingeri et al. 2014a). For instance, if the garment that we are wearing becomes wet, a chill or cold feeling will be sensed directly on the skin, due to the cooling effect of evaporation of the liquid and/or the increased thermal conductivity of the fabric. At the same time, the clingy or sticky sensation detected by the cutaneous tactile receptors, occurring when the wet material moves intermittently against and across the skin, is combined with the cold sensations in the brain. At this point, the brain, being already familiar with these types of feeling (cold and clingy), recognises the presence of a wet material on the skin (Bentley 1900; Filingeri and Havenith 2015; Bergmann Tiest 2015) resulting in a perception of wetness.

Clothing innovations and advances usually involve the use of textile performance enhancing technologies, validated by standard material test methods conducted with specially developed apparatus. Although these methods allow assessments of objective improvements in material performance, it is often unknown whether these relate to perceivable improvements in wear comfort in real use. The end goal of the clothing industry is to reduce wear discomfort during exercise. Therefore, the adoption of an integrative paradigm where the assessment of textile and clothing parameters (instrumentally measured) is undertaken using human physiological as well as perceptual responses would be of great value. In this regard, recently, in a series of studies in which fabrics were applied to a limited skin area (skin regional studies), the individual and combined role of fabric thickness (static skin contact) and surface texture (dynamic skin contact) on skin wetness perception was investigated (Raccuglia et al. 2016a; Raccuglia et al. 2016b; Raccuglia et al. 2017a; Raccuglia et al. 2017b). In the static skin application condition, the role of fabric thickness as major determinant of fabric absorption capacity and wetness perception was demonstrated (Raccuglia et al. 2016a; Raccuglia et al. 2016b). Specifically, when applying the same relative to volume water content ($mL \cdot mm^{-3}$; same saturation percentage) thicker fabrics were perceived wetter than the thinner ones. Conversely, when adding the same absolute water amount ($mL \cdot mm^{-2}$), thicker fabrics were perceived dryer compared to thinner fabrics, given that thinner fabrics were more saturated. The individuals could perceive various degrees of fabric wetness by integrating fabric thermal (cooling provided) and mechanical (load on the skin) inputs sensed at the skin by thermo- and mechanoreceptors, respectively. Specifically, with the increase in fabric water content the cooling power also increases, resulting in higher local skin cooling (reduction in skin temperature) and wetness perception. The contribution of fabric tactile input was indicated by greater wetness perception in heavier fabrics at equal water content, due to the resultant higher load/pressure which increases the magnitude of stimulation of both thermo- and mechanoreceptors. Finally, as expected (Fukazawa and Havenith 2009; Gerrett et al. 2013), sensations of discomfort were strongly correlated to fabric wetness perception, showing the importance of this parameter in overall comfort sensation

In a dynamic skin contact investigation (Raccuglia et al. 2017b; Raccuglia et al. 2017a), i.e. when the fabrics move across the skin, the role of fabric surface properties on wetness perception was studied. It was observed that wet fabric materials with a smoother surface resulted in greater skin wetness perception compared to the wet rougher fabric surfaces. In fact, when moving across the skin, the wet smoother materials may cause higher cutaneous displacement compared to the rougher ones. The higher skin displacement likely resulted from a higher adhesiveness between the wet fabric and skin, which in turn was caused by the creation of a greater number of contact points offered by the smoother fabric surface. The magnitude of skin displacement was detected by the cutaneous tactile receptors as higher or lower stickiness or clinginess sensation and, subsequently associated with different degrees of fabric wetness. Interestingly, the power of wetness perception prediction became substantially stronger when including, both stickiness sensation and fabric thickness as predictors.

Due to the critical impact that stickiness sensation was shown to have on wetness perception in the skin regional study (dynamic contact), the aim of the current study was to investigate the influence of both stickiness sensation and wetness perception on wear discomfort, in a whole-body study. In the current study garment wetness was induced by physical exercise (sweating), rather than by manipulating the fabric moisture content by adding water to it, as done in earlier experiments (Raccuglia et al. 2016a; Raccuglia et al. 2017b). The latter difference between whole body (exercise) and the skin regional studies adds an extra different type of thermal sensory cue, which can contribute to the ability to perceive different degrees of fabric wetness. In fact, in the current whole body investigation, the contribution of the cooling effect arising from the evaporation of sweat, induced by physical exercise, was examined. In contrast, in the earlier studies (skin regional study), water evaporation from the fabrics, during the application to the skin, was prevented by covering the fabrics with a thin PVC layer. Therefore, in the skin regional studies, the role of cooling sensations mainly arouse from the increased thermal conductivity of the wetted fabrics.

To solely study the role of fabric stickiness and wetness perception on wear discomfort during physical exercise, three experimental garments were selected and matched for their physical parameters. To induce substantial differences in stickiness and wetness sensations, the fabric surface area in contact with the skin between the three garments, was manipulated. It was hypothesised that higher garment surface area in contact with the skin will result in greater stickiness sensation and wetness perception and that these latter two will impact wear discomfort. However, manipulations of fabric contact surface area could also affect the surface area available for sweat absorption between the three garments, this leading to differences in garments absolute sweat content and moisture saturation. Therefore, the current study examined the combined role fabric contact area with the skin, fabric sweat content and moisture saturation percentage on stickiness sensation and wetness perception.

6.2 Method

6.2.1 Participants

Eight young (21.4 ± 2.3 yrs.) males recreationally active (strength and conditioning as well as aerobic exercises at least 4 times per week) and of Western European origin participants, were recruited from the Loughborough University student cohort. Their mean body mass, height and body fat was, 81.0 ± 10.1 kg, 181.1 ± 8.1 cm and 15 ± 3.7%, respectively.

The experimental procedures where fully explained to the participants verbally and in writing, before obtaining informed written consent and completing a health screening questionnaire. All the experimental procedures involved were approved by the Loughborough University Ethical Committee. The study was conducted within the confines of the World Medical Association Declaration of Helsinki for medical research involving human participants.

6.2.2 Garments

The experimental garments included three short sleeved 100% polyester T-shirts with identical design and fit (loose). Three fabrics were selected to produce the three experimental garments. The fabrics were matched for thickness, mass, denier count, fibre content, and finish (hydrophilic finish) (Table 1). The main difference between the three fabrics was in the percentage of surface area in contact with the skin (contact surface area; Contact-SA; Table 1). The latter was achieved by knitting the three fabrics using different mesh structures, each of these characterised by holes of different diameters (Fig 1): high (HIGH), medium (MEDIUM) and low (LOW) Contact-SA. Consequently, these differences in Contact-SA led to differences in surface area available for sweat absorption.

Garment Contact-SA was calculated using a high resolution picture of each fabric with a white background (‘holes’ area). The creation of high contrast between the fabric and the white background allowed measurements of the ‘holes area’ in unit of pixels, using Adobe Photoshop Software (2017). The Contact-SA was calculated as percentage of the full area of the fabric (in the picture) by subtracting the total area. The Contact-SA expressed as percentage of the ‘holes area’ was 92.7%, 87.5% and 66.3%, for HIGH, MEDIUM and LOW, respectively.

Due to differences in Contact-SA, the total capacity to absorb liquid moisture (absorption capacity; ABS in g·m^{-2}) was different across the three fabrics (Table1) and therefore garments.

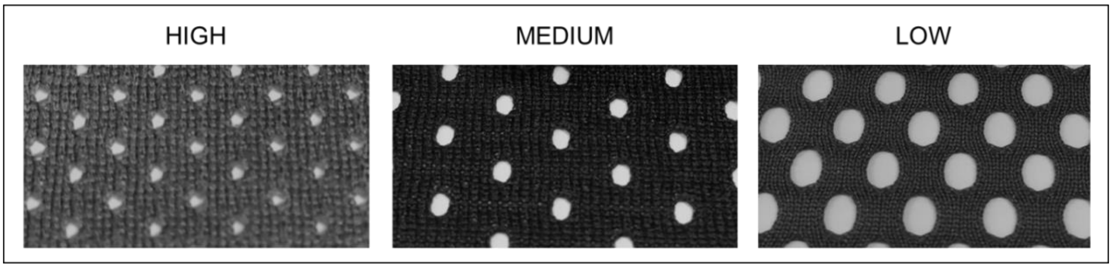

Figure 1 High resolution photographs of HIGH (high Contact-SA), MEDIUM (medium Contact-SA) and LOW (low Contact-SA) fabrics.

Table 1 Experimental fabrics/ garment specifications.

Fabrics/ Garment	Fibre type	Thickness (mm)	Fabric Mass (g·m^{-2})	Structure	Denier count	Sample Contact-SA (%)	Sample ABS (g·m^{-2})
HIGH	100% pes	0.56	85	single jersey, mesh (filament)	50	92.7	278
MEDIUM	100% pes	0.56	85	single jersey, mesh (filament)	50	87.5	266
LOW	100% pes	0.56	80	single jersey, mesh (filament)	50	66.3	172

HIGH = high contact surface area, MEDIUM = medium contact surface are, LOW = low contact surface area. 100 % pes = 100% polyester; Contact-SA = contact surface area calculated with Photoshop Software (2017) subtracting the ‘holes area’ from the total surface are; ABS = moisture absorption capacity.

6.2.3 Experimental protocol

Pre-test. Participants were required to attend the Environmental Ergonomics Research Centre for a pre-test, involving anthropometric measurements of height, body mass (Mettler Toledo Kcc150, Mettler Toledo, Leicester, UK), percentage of body fat (Tanita Corporation, Tokyo, Japan) and body dimensions for the anthropometric assessments of the adequate garment size used for the experimental trials.

During the pre-test participants also performed a 20-min running test on a treadmill (h/p/cosmos mercury 4.0, h/p/cosmos Sport & Medical GmbH, Nussdorf-Traunstein, Germany). During this time the participants were asked to select the speed they could comfortably run for 1 hour. The selected speed (10.2 ± 0.9 km·h^{-1}) was then recorded and used for the following experimental trials.

Experimental trials. Participants performed 3 running trials on different days, separated by a minimum of 24 hours of rest. In each trial one of the three experimental garments (HIGH, MEDIUM and LOW) was worn. The testing sequence was counterbalanced to minimise any order effect and each participant performed the trials at the same time of the day to minimise circadian variation. Participants ran at the pre-set fixed speed for 30-min. This running duration was selected to replicate the type of activity typically performed in an indoor environment e.g. at the gym. Participants were instructed to refrain from strenuous exercise, abstain from caffeine and alcohol consumption 24 hours before testing, and to keep a record of their food intake and replicate it the day before each visit. In order to maintain euhydration, they were also advised to consume 20 mL·kg^{-1} body weight of water during the two hours prior to testing. On arrival to the laboratory participants were asked to void their bladders and self-insert a rectal probe, to monitor changes in body core temperature. The rectal probe (Grant Instrument Ltd, Cambridge, UK) was inserted 10 cm beyond the anal sphincter and rectal temperature was measured throughout each experimental trial at 1-min intervals and recorded via a portable data logger (Grant Instrument Ltd, Cambridge, UK) connected to the thermistor's probe. Participants also wore a wrist-based heart rate (HR) monitor (Polar A360, Polar Electro Oy, Professorintie 5, Kempele, Finland) and HR was recorded before (BASELINE) and during the running trials at 1-min intervals. A wrist-based monitor, rather than a chest-based strap, was used since a chest strap would have interfered with sweat transfer from the skin to the T-shirt. Following from this, semi-nude (including underwear, rectal probe and HR monitor) body mass was recorded. Subsequently, participants were provided with standard running shorts and socks, worn with their personal running shoes, and were asked to use the same personal gears for the entire duration of the experiment. This period of preparation lasted approximately 15-min and allowed time for the stabilisation of HR and T_{core}. Participants moved to the climatic chamber, rested standing still on the treadmill and after 10-min baseline HR was recorded. They then donned the experimental garment and the running trial started. In order to prevent dehydration, the participants were allowed to drink water *ad libitum* during the experiment, and liquid consumption was recorded. At the end of the run participants took off the worn T-shirt and hand it over to the experimenter for measurements of post-exercise garment mass. The participants took off shorts, socks and shoes, towelled their skin (this took ~ 2-min) and post-exercise semi-nude body mass was recorded.

Sweat production was calculated based on the weight change of each participant (gross sweat loss, GSL), corrected for liquid intake, and reported in grams per body surface area ($g \cdot m^{-2}$), according to:

$$\text{GSL } (g \cdot m^{-2}) = [w_{b1} - (w_{b2} - liquid)]/SA$$

Where;

w_{b1} body mass at the start of the experiment (g)

The experiment was conducted in a climatic chamber maintained at 27.4 ± 0.3 ^{o}C, 49.4 ± 3.4 % relative humidity. Apart from having different contact areas, the three garments presented different ventilation potentials, as results of the three different mesh structures. Thus, to cancel-out the effect that the presence of relatively high air flow could have had on sweat evaporation and perceptual responses (i.e. wetness perception, thermal sensation and wear discomfort), environment air flow was set to negligible levels ($0.2\ m \cdot s^{-1}$).

6.2.4 Perceptual measurements

During each experimental trial wetness perception, stickiness sensation, thermal sensation, texture sensation and wear discomfort were scored by the participants at 5-min intervals using interval scales (Fig 2). Wetness perception was scored using an ordinal unipolar scale ranging from 0 (extremely dry) to 30 (extremely wet) (Raccuglia et al. 2016a; Raccuglia et al. 2017b). Stickiness sensation was scored using a 12-points ordinal unipolar scale (0 not -sticky, 12 extremely sticky) (Raccuglia et al. 2017b). Thermal sensation was scored using an ordinal bipolar scale ranging from -10 Cool to 20 Hot, modified from (Raccuglia et al. 2016a).

In the dynamic skin regional study (Raccuglia et al. 2017b), it was observed an increase in texture sensation when the fabric became wet (i.e. the fabric is perceived rougher than when dry). Interestingly this increase in texture sensation was associated with reductions in pleasantness sensation. Hence, in the current experiment fabric texture sensations were recorded to assess whether these had an impact also on wear discomfort. Fabric texture sensation was scored with an ordinal bipolar scale (from -9 very smooth to 9 very rough) according to Raccuglia et al. (2017b).

Finally, the increase in wear discomfort was scored using an ordinal unipolar scale, ranging from 1 comfortable to 7 very uncomfortable (Fig 2).

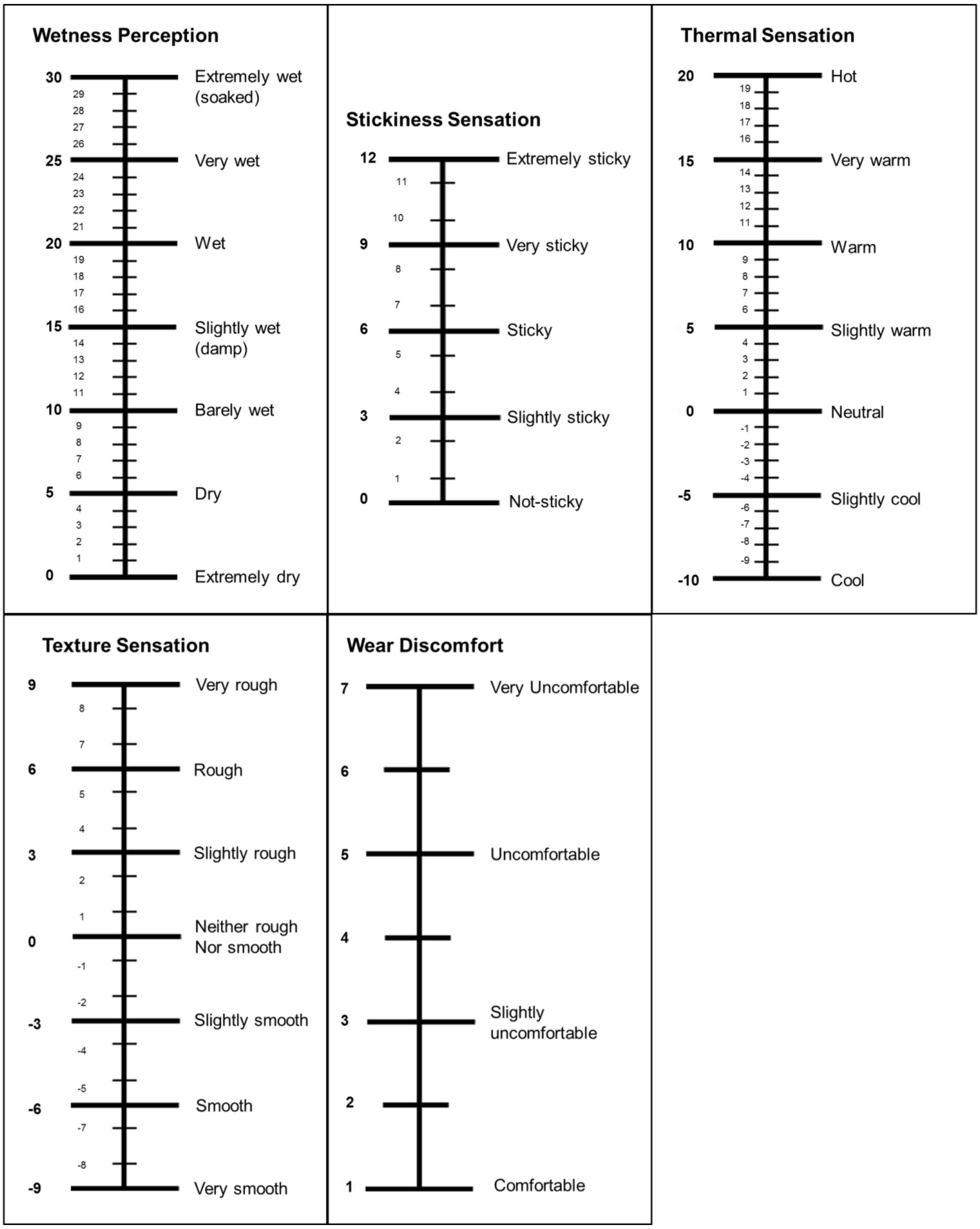

Figure 2 Perceptual scales (Raccuglia et al. 2016a; Raccuglia et al. 2017b). Participants scored each perceptual parameter by reporting verbally the selected number; each score was then recorded by the investigator.

6.3 Statistics

The independent variables were: HR and T_{core} (physiological) and wetness perception, stickiness sensation, thermal sensation, texture sensation and wear discomfort (sensorial).

Data were tested for normality of distribution and homogeneity of variance with Shapiro-Wilk and Levene's tests, respectively.

One-way repeated measures ANOVA tests were performed to assess differences in HR, $T_{core,}$ GSL and $SWEAT_{ABS}$ between the garments (HIGH, MEDIUM and LOW). When statistical differences were observed *post hoc* tests with Bonferroni correction for multiple comparisons were conducted.

Wetness perception, stickiness sensation, texture sensation and wear comfort data were measured through means of ordinal scales and also violated the assumption of normality of distribution, therefore for the statistical analysis non-parametric tests were conducted.

Friedman tests were conducted to assess the effect of garment contact area (HIGH, MEDIUM and LOW) and therefore absolute sweat absorption ($g \cdot m^{-2}$) as well as saturation (% of absorption capacity) on wetness perception, stickiness sensation, texture sensation and wear comfort at each of the run time points (BASELINE, 5 MIN, 10 MIN, 15 MIN, 20 MIN, 25 MIN, 30 MIN). When statistical differences were observed Wilcoxon Signed Rank tests were conducted.

To assess the impact of wetness perception, stickiness sensation, thermal sensation and texture sensation (independent variables) on wear discomfort (dependent variable), stepwise regression analyses were performed.

In all analyses $p < 0.05$ was used to establish significant differences. Data are reported as mean ± standard deviation. Statistical analysis was performed using the software IBM SPSS Statistics version 23 (IBM, Chicago, USA).

6.4 Results

6.4.1 Sweat produced

The amount of total sweat produced (GSL) at the end of the each run condition was not affected by the type of garment worn, therefore no significant ($p > 0.05$) differences were observed in GSL between HIGH, MEDIUM and LOW (Fig 3).

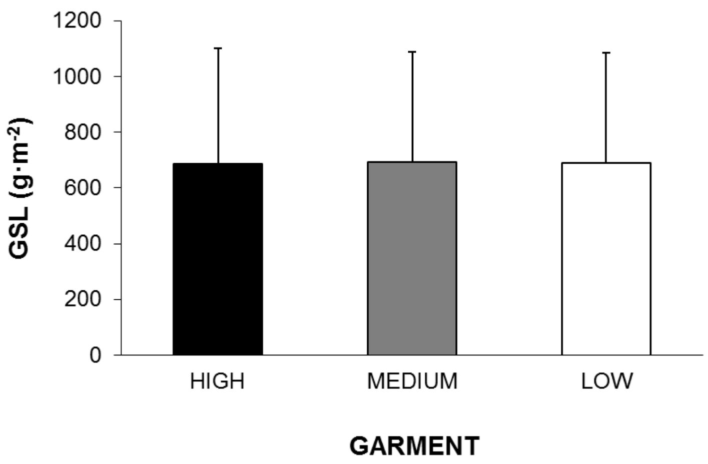

Figure 3 Gross sweat loss (GSL) data between the three experimental garments (HIGH; MEDIUM; LOW). No significant differences in GSL were observed between the three garments.

6.4.2 Heart rate and core temperature

HR and T_{core} were recorded every 1-min intervals and the average data of 5-min for HR are reported (Fig 4A). There were no significant differences ($p > 0.05$) in HR (Fig 4A) or T_{core} (Fig 4B) between HIGH, MEDIUM and LOW.

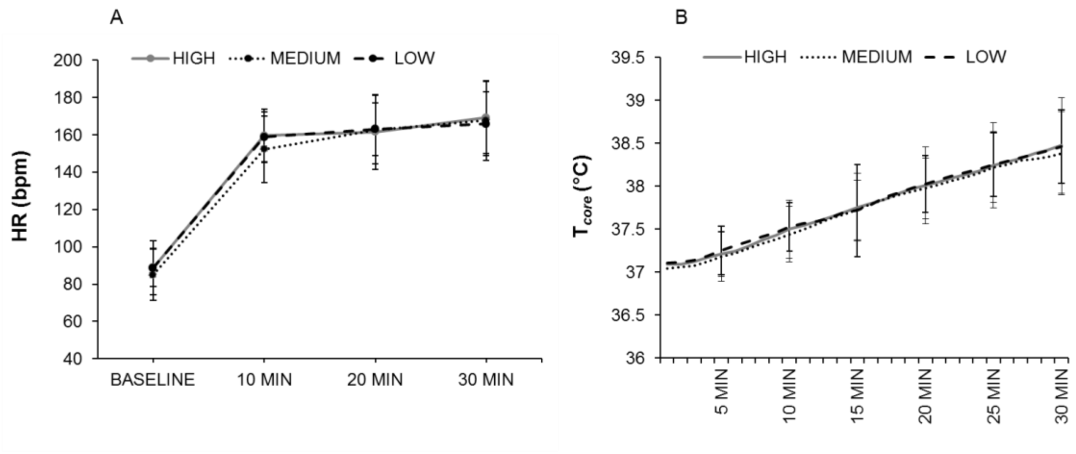

Figure 4 Time course (Baseline - 30 MIN) of heart rate (HR; 4A) and core temperature (T_{core}; 4B). No significant differences In HR or T_{core} were observed between the 3 garments (HIGH, MEDIUM and LOW).

6.4.3 Sweat absorbed

Garment type had a significant effect ($p = 0.04$) on sweat absorption (Fig 5A). Specifically, LOW showed a significantly lower ($p = 0.02$) absolute sweat content ($SWEAT_{ABS}$) compared to HIGH, whereas no significant differences where observed between LOW and MEDIUM ($p = 0.09$), neither between HIGH and MEDIUM ($p = 0.54$).

LOW was significantly more saturated ($p = 0.01$) then HIGH (34% and 21%, respectively). However, garment saturation in MEDIUM (25%) was not significantly different from HIGH ($p = 0.4$) or LOW ($p = 0.08$) (Fig 5B). Despite the lack of significance, between MEDIUM and LOW a trend was visible for difference in sweat absorption and saturation to develop ($p < 0.1$).

Given that garment sweat absorption ($SWEAT_{ABS}$) and garment saturation in MEDIUM were not significantly different from HIGH and LOW, MEDIUM was not taken into account for the following analyses.

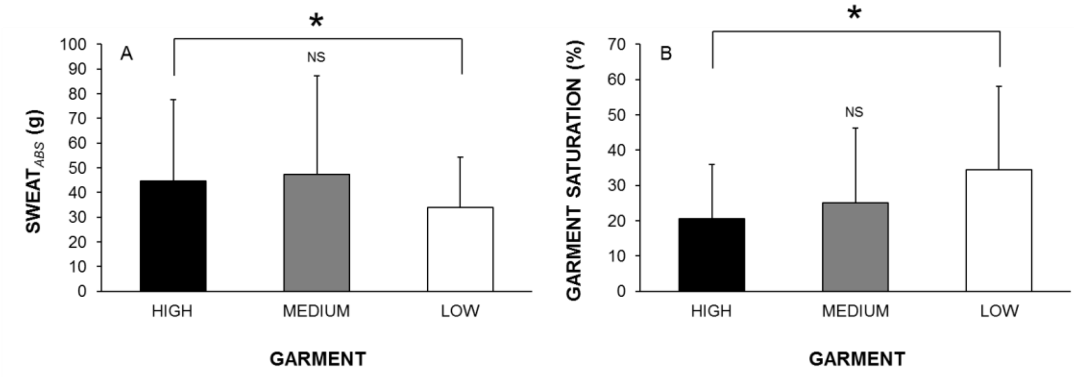

Figure 5A Absolute amount of sweat (SWEAT$_{ABS}$) absorbed by the three garments (HIGH, MEDIUM and LOW). Significantly (* $p = 0.02$) low SWEAT$_{ABS}$ in LOW compared to HIGH. **5B** Percentage of sweat saturation in each garment (HIGH, MEDIUM and LOW). Significantly (* $p = 0.01$) high sweat saturation in LOW compared to HIGH.

6.4.4 Wetness perception and stickiness sensation

Wetness perception (Fig 6A) was not different ($p > 0.05$) between HIGH and LOW at any of the analysed time points (BASELINE-30 MIN). On the other hand, stickiness sensation (Fig 6B) was significantly different ($p < 0.05$) between the two garments at each time point, apart from BASELINE and 5 MIN ($p > 0.05$). Specifically, stickiness sensation was greater in the garment with lower Contact-SA (LOW), which was also more saturated (Fig 5B).

6.4.5 Thermal sensation, texture sensation and wear discomfort

There were no significant ($p > 0.05$) differences in thermal sensation (Fig 6C) between HIGH and LOW. On the other hand, significant differences ($p < 0.05$) in texture sensation (Fig 6D) were observed between HIGH and LOW at each analysed time point (BASELINE - 30 MIN). Specifically, texture sensation was higher in LOW compared to HIGH (LOW was sensed as more texturized and rougher).

Wear discomfort was significantly higher in LOW compared to HIGH ($p < 0.05$) at all the analysed time points (Fig 6E).

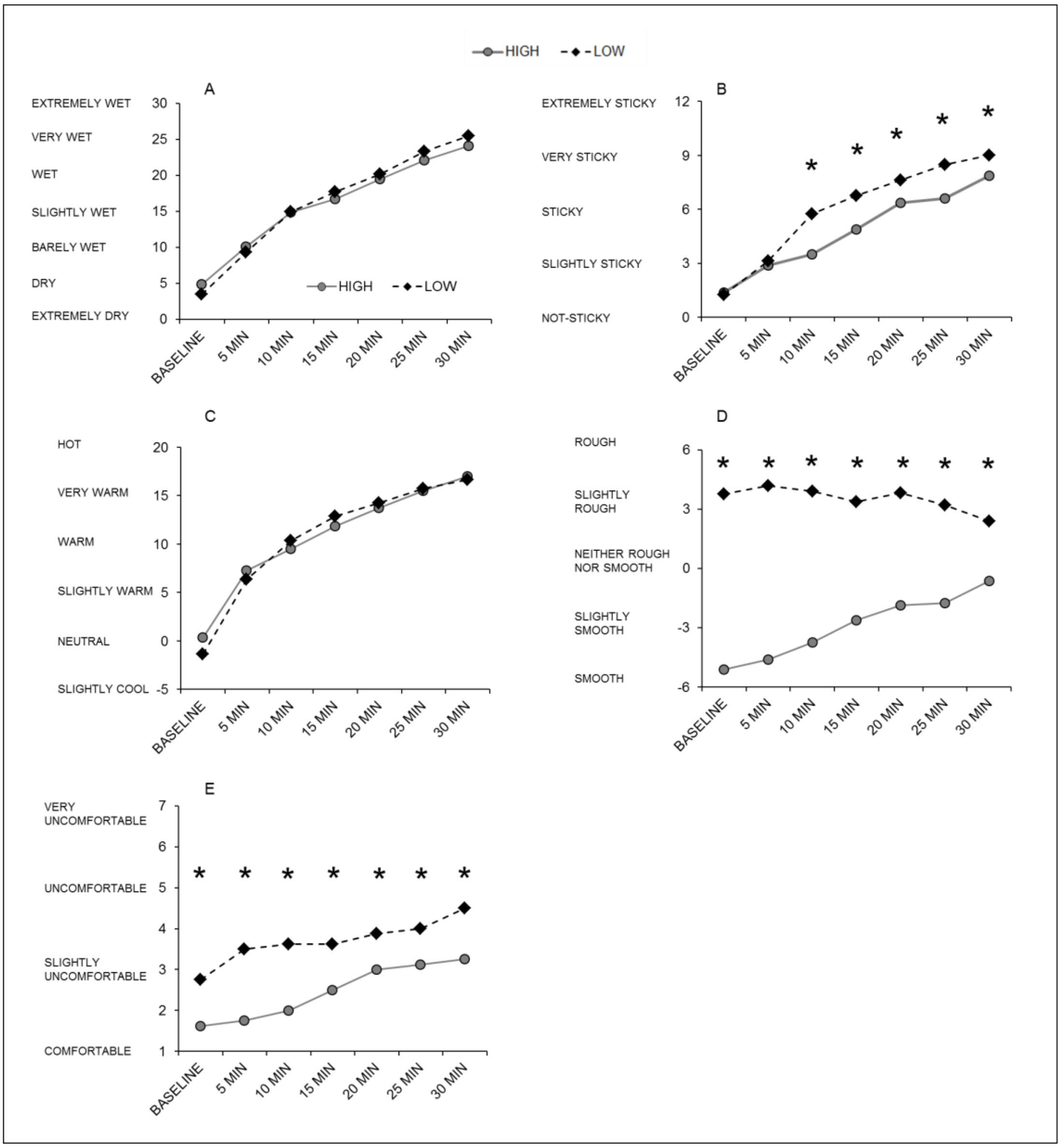

Figure 6 (A) Wetness perception, **(B)** Stickiness sensation, (**C)** Thermal sensation, **(D)** Texture sensation and **(E)** Wear comfort over time (BASELINE-30 MIN) of the two experimental garments (HIGH and LOW). * indicates significant differences ($p < 0.005$) between the two garments.

6.4.6 Factors causing discomfort

Stepwise regression analyses were conducted to identify the factor/s influencing wear discomfort at BASELINE and at 10-, 20- and 30-MIN of exercise activity. For this analysis data from HIGH, MEDIUM and LOW conditions were included. Wetness perception, stickiness sensation, thermal sensation and texture sensation were selected as independent variables and wear discomfort as dependent variable. The analysis was conducted separately for BASELINE, 10 MIN, 20 MIN and 30 MIN to cancel out a potential time-effect on the prediction models.

Texture sensation was selected as the best predictor of wear discomfort at BASELINE (Fig 7A) (r^2 = 0.30, p = 0.019). Liner positive relationships were observed between wear discomfort and texture sensation also at 10 MIN (Fig 7B) (r^2 = 0.33, p = 0.019), 20 MIN (Fig 7C) (r^2 = 0.28, p = 0.019) and 30 MIN (Fig 7D) (r^2 = 0.22, p = 0.018). However, the power of wear discomfort prediction at 10 MIN (Fig 8B), 20 MIN (Fig 8C) and 30 MIN (Fig 8D), was stronger when selecting stickiness sensation as predictor. Specifically, stickiness sensation explained 36% (r^2 = 0.36, p = 0.02), 56% (r^2 = 0.56, p = 0.001) and 59 % (r^2 = 0.59, p = 0.001) of the variance in wear discomfort at 10 MIN, 20 MIN and 30 MIN of running, respectively. Nevertheless, stickiness sensation did not affected wear discomfort at BASELINE (Fig 8A) (r^2 = 0.04 p = 0.34).

A regression analysis for wear discomfort, including all data points did not produce a predictive model. A potential reason for this could be a time effect, i.e. certain parameters are relevant for wear (dis)comfort at specific time points. For this reason, analysis at different experimental stages was performed, and the critical contribution of texture sensation and stickiness at different stages was observed.

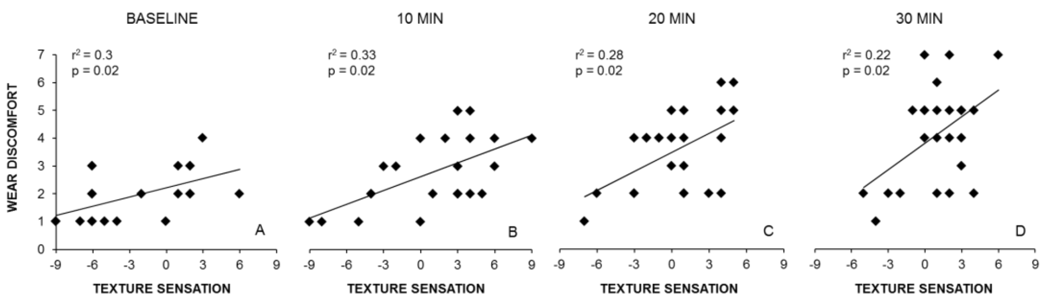

Figure 7 Prediction models of wear discomfort at BASELINE (7A), 10 MIN (7B), 20 MIN (7C) and 30 MIN (7D), using texture sensation as predictor. To predict wear discomfort stepwise linear regression analyses were performed separately for each selected time point.

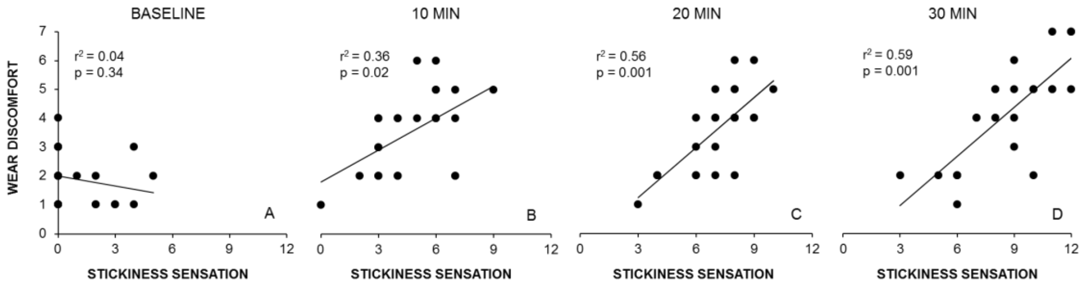

Figure 8 Prediction models of wear discomfort at BASELINE (8A), 10 MIN (8B), 20 MIN (8C) and 30 MIN (8D), using stickiness sensation as predictor. To predict wear discomfort stepwise linear regression analyses were performed separately for each selected time point.

6.5 Discussion

In this study we used an integrative approach where moisture-handling properties of textile materials were assessed through changes in wear comfort during exercise. In particular, the potential impact of garment surface area in contact with the skin on wetness perception and stickiness sensation was investigated. Manipulations of fabric contact area caused differences in the fabric area available for sweat absorption. Consequently, these changes lead to differences in garment sweat content and saturation (percentage of total absorption capacity), the latter affecting perceptual responses. Additionally, the influence of wetness perception, stickiness sensation, thermal sensation and texture sensation on wear discomfort during physical exercise was explored. While in a research-based environment it is common to conduct human wear testing, this experiment clearly demonstrated the value for the clothing manufactures to also use a paradigm in which clothing development involves an additional human-focused evaluation process, rather than ending at the material evaluation level.

6.5.1 Sweat produced and sweat absorbed

The performed running exercises led to the same sweat production between the three experimental conditions (HIGH, MEDIUM and LOW garment) however, different sweat contents were achieved between the garments. Specifically, the LOW contact surface area garment, showed the lowest sweat content (34 g) but, due to the lowest contact surface area available for sweat absorption, it was also the most saturated (34%). The latter was followed by MEDIUM and HIGH contact surface area garments, which due to the higher contact surface area, presented greater absolute sweat content (47 g and 45 g respectively) while being less saturated (27% and 21 %, respectively).

As expected, the differences observed in garment sweat content and saturation did not affect the physiological responses of core temperature and heart rate.

6.5.2 Thermal sensation

Variations in thermal sensation between the garments, which could have occurred as result of different sweat content and ventilation potentials, were successfully controlled. In fact, thermal sensation was not different between the three garments, likely due to the deliberately low air flow in the environment.

6.5.3 The role of fabric contact area

In a study where pre-wetted fabrics were applied in dynamic contact with the inner forearm, it was observed that sensations of stickiness of wet fabrics can be exacerbated when using fabrics with smoother surface texture (Raccuglia et al. 2017b). Specifically, when moving across the skin, the wet smoother fabric surfaces would have created higher level of contact with the skin, resulting in higher skin displacement and associated with higher stickiness. According to this, in the current study it was hypothesised that the level of fabric surface area in contact with the skin would have had an impact on stickiness sensation and consequently wetness perception, with more contact area increasing stickiness sensation and wetness perception. However, in the current experiment, the opposite was observed, with low fabric contact area inducing higher stickiness sensation. Specifically, when reducing the amount of fabric area in contact with the skin, less fabric area for sweat absorption was available. Indeed, higher moisture saturation percentage was observed in fabric with lower fabric contact area, this subsequently leading to a greater stickiness sensation. Therefore, while fabric surface texture can affect stickiness sensation and related discomfort through changes in fabric contact area with the skin (Raccuglia et al. 2017b), it is also important to consider the consequences of the contact area for moisture absorption and saturation as well. In fact, fabric moisture saturation may be the real cause for the current findings and may have 'overruled' the impact of contact area. Similar to other multifactorial systems (Lloyd et al. 2016), the current findings suggest that in a human-clothing system the integration and also the strength of different cutaneous stimuli, triggered by various textiles parameters, should be considered.

6.5.4 Stickiness sensation and wetness perception

The differences in saturation and sweat content between the LOW and HIGH garments, achieved through manipulations of fabric contact area (and therefore fabric area available for absorption), resulted in significant differences in stickiness sensation. Specifically, stickiness sensation was higher in the LOW T-Shirt, despite presenting a lower absolute sweat content, compared to the HIGH one. The finding might appear controversial when looking at the absolute data (sweat absorption in grams), however when considering sweat content as percentage of the absorption capacity of the garment (maximum amount of liquid moisture that can be absorbed by the garment), it can be observed that the LOW garment (lower contact surface area and lower absorption capacity) was more saturated than HIGH (higher contact surface area and higher absorption capacity), this resulting in greater stickiness sensation. The current findings are in line with recent observations (Raccuglia et al. 2016a), which led to conclude that fabric saturation, rather than the absolute moisture content, is a better parameter to consider when studying moisture properties of fabrics (even if unmatched for thickness or volume).

Despite the significant differences in sweat content, saturation percentage and also stickiness sensation, wetness perception was almost identical between the two garments. The latter was unexpected, since recently a strong positive relationship between stickiness sensation and wetness perception was observed in a skin regional study (Raccuglia et al. 2017b). Wetness and humidity can be perceived on the skin through the combinations of cold sensations (i.e. sweat evaporation and/or contact with a liquid colder than then skin) and tactile sensations (i.e. stickiness or clinginess) (Bergmann Tiest et al. 2012b; Filingeri et al. 2014a). In the skin regional studies, fabric moisture content was manipulated by adding water at room temperature to the fabric, this substantially increasing the thermal conductivity of the fabric and acting as cold cue for wetness perception. On the other hand, it seems that during exercise in warm ambient temperature, sweat evaporation did not provide enough cooling, typically considered one of the thermal cues involved in the perception of skin wetness (Niedermann and Rossi 2012). Therefore, the current results indicate that when performing physical exercise in warm environments, differences in garment stickiness sensation do not necessarily affect wetness perception. Consequently, in a mild or hot environment, when cold sensory cues are restricted, stickiness sensation seems a more impactful parameter to consider when determining moisture-related differences between garments.

6.5.5 Wear discomfort

The other aim of the current study was to identify the factor/s influencing discomfort during wear. Whilst no overall model for discomfort across all data could be developed (suggesting complex interactions between the relevant parameters and the time-course development of the relationships), models for different time points were produced. The results showed that at baseline, when the individuals just donned the garment, wear discomfort is in part affected by sensations of fabric texture. Specifically, the LOW garment (low contact surface area) was perceived significantly rougher than the HIGH garment (high contact surface area). In fact, the lower contact surface area, given by the presence of larger holes in the LOW fabric, might have led to a fabric with a high number of edges, causing noticeable sensation of roughness. The latter is illustrated in figure 6D, which also suggests that this effect diminishes over time, mostly likely due to the effect of moisture absorbed in different fabrics. The influence of texture sensation on wear discomfort, during the initial interactions of the garment with the skin, explains why garment texture may be a parameter partially affecting the buying decision process of a specific clothing product.

With the start of the physical exercise, another factor appears to contribute to the increase in wear discomfort. In fact at 10-min, 20-min and 30-min of running exercise, stickiness sensation was selected as the main parameter affecting wear discomfort.

Texture sensation explained 30% of the variance in wear discomfort at baseline whereas during exercise stickiness sensation (at 10-min, 20-min and 30-min) explained approximately 50% of the variance in wear discomfort. As such, although the current study successfully identified factors that can contribute to wear discomfort at rest and during exercise, a substantial amount of variance in discomfort (~ 50%) still needs to be explained. The achieved predictive power, however, seems reasonable, given the complexity of the environment-human-clothing system in which the sensation of wear comfort results from the interaction of a number of different factors. For this reason, future investigations should address the role that other parameters could play on wear discomfort, to achieve more accurate estimations of wear comfort and to improve clothing performance.

6.6 Conclusions

The current findings indicated that when the reduction in fabric contact area percentage causes a decrease in the area available for sweat absorption i.e. in a mesh material, a fabric with higher sweat saturation percentage is obtained. Higher sweat saturation percentage will then cause greater stickiness sensations, despite lower contact area (typically associated with lower stickiness). This suggests that, when studying moisture-related responses in humans, it is important to consider the interaction of different textile parameters, as in this case the combined effect of fabric contact area and moisture saturation percentage.

Factors influencing perception of wear discomfort can change over time and in relation to the over-time changes in human thermophysiological responses, such as metabolic rate and sweating. These changes will in turn affect moisture and haptics responses in humans, leading to a highly complex model of wetness perception in relation to textile materials. Specifically, during exercise in warm conditions, the achieved changes in garment sweat content and saturation resulted in significant differences in stickiness sensation. Nevertheless, these differences did not impact wetness perception responses in the warm environmental condition examined. In fact, in a warm environment (no air movement) and during exercise, the cold sensations, arising from sweat evaporation, may not be sufficient to allow discriminations between the two moisture levels in the garments. On the other hand, differences in stickiness between the two garments were clearly sensed. This indicates that stickiness sensation might represent a more impactful parameter to consider. Consequently, stickiness sensation was indicated as parameter in part (~ 50%) affecting wear discomfort during physical exercise, whereas wetness perception itself did not significantly contribute to the variation in wear discomfort in the tested conditions. Additionally, during the first contact with the skin, when the garment is still dry, the sensation of fabric texture was indicated as the main parameter contributing to wear (dis)comfort.

The clothing industry tends to end the development process at the material tests level, due to cost and/or time-related reasons. In line with a research-focused approach, this study highlighted, in human wear testing, the subjective sensations which are sources of wear discomfort during physical exercise. Therefore, in order to assess the impact of textile innovations on wear (dis)comfort, the process of clothing development should include a human evaluation level, rather than ending at the material testing level. This could lead to paradigm shift in clothing development, resulting in a human-orientated design process.

Future studies should account for additional critical factors contributing to wear discomfort during exercise and take into account other environmental conditions (i.e. outdoor cold conditions), in order to advance predictions of wear discomfort and the development of sportswear as well as protective clothing.

When considering the multifactorial nature of wear comfort, complementary data also examining the factors influencing it at the moment of the purchase (shop setting) and post-exercise, are necessary. This will potentially lead to a holistic model of wear comfort in an environment-human-clothing system.

CHAPTER 7

Laboratory study 5

Spatial and temporal migration of sweat: from skin to clothing

CHAPTER SUMMARY

Building on previous work on mapping sweat production across the body, this study aimed to obtain detailed spatial and temporal maps showing how this sweat migrates into a single clothing layer (T-Shirt) during physical exercise. Eight male participants performed running exercise in warm environment. Garment sweat absorption was mapped over a total running time of 50-min, in 10 separated running trials of different duration (5 min increments). After running, the garment was dissected into 22 different parts and local sweat absorption (ABS_{local}) was quantified by weighing each garment part before and after drying. From ABS_{local}, garment total sweat absorption (ABS_{total}) was estimated. Clear patterns of sweat absorption reduction from superior-to-inferior and from medial-to-lateral T-Shirt zones were observed, with the mid back medial and the low front hem showing the highest, respectively. Quantitative data on garment total and regional sweat absorption were obtained and considerable variation between different garment zones was identified. These data can support the development of sport and personal protective clothing with the end goal to prevent workers heat-related injuries as well as maximise human performance and productivity.

7.1 Introduction

Humans wear clothing as means of embellishment, status and modesty. More importantly for human health and survival, clothing provides the body with a protective physical barrier from environmental factors, such as rain, snow, wind and solar radiation. Beside this imperative protective function, the interaction between clothing and the human body has implications in terms of biophysics of heat transfer, temperature regulation and comfort (Havenith 1999; Morrissey and Rossi 2013b; Jay and Brotherhood 2016). When exposed to hot environments, sweat evaporation occurs to maintain body thermal balance, representing the greatest avenue for body heat loss in exercise (Candas et al. 1979). However, the clothing barrier impairs evaporative heat loss from the body, this in part causing less efficient sweat evaporation (Candas et al. 1979; Shapiro et al. 1982; Havenith et al. 2007b; Havenith et al. 2013). Once body heat production or the evaporative resistance of clothing increases to the point where sweat evaporation cannot keep up with sweat rate, the skin becomes saturated with sweat and the garment worn will also get wet. In the cold and/or when metabolic heat production is reduced right after physical exercise, skin and clothing wetness cause a fast decrease in body temperatures (Li 2005). In this scenario, both skin and clothing wetness can lead to thermal discomfort, cold sensations and, in extreme conditions, to hypothermia.

Apart from its impact on body heat loss, the presence of wetness also exacerbates the tactile interaction between the skin and the fabric, sensed by the wearer as stickiness (Filingeri et al. 2015; Raccuglia et al. 2017b). Hence, wetness represents one of the most important sources of discomfort when wearing clothing, (Hong et al. 1988; Raccuglia et al. 2016a) which could even contribute to decrements in human performance and productivity (Parsons 2014; DenHartog and Koerhuis 2017).

Extensive research has been conducted to discover strategies able to maximise heat and mass transfer through the clothing barrier, yet maintaining its protective function (Lomax 2007; Fukazawa and Havenith 2009; Sarkar et al. 2009; Havenith et al. 2011; Ke et al. 2013; Sun et al. 2015; Lin et al. 2015; Wang et al. 2017). To characterise fabric moisture absorption and transport properties, several apparatus and test methods have been developed (Harnett and Mehta 1984; Hong et al. 1988; Ghali et al. 1994; McCullough et al. 2003; Huang and Qian 2007; Jianhua Huang and Xiaoming Qian 2008), however the relevance of these tests has not been supported by real life data from humans during exercise. Previous studies have provided data of regional sweating rates in humans during rest and exercise (Cotter et al. 1995; Taylor et al. 2006; Machado-Moreira et al. 2008a; Machado-Moreira et al. 2008b; Machado-Moreira et al. 2008c; Smith and Havenith 2011; Smith and Havenith 2012). These data made available fundamental knowledge on sweat rate patterns across the human body that might support the process of sportswear and protective clothing development. Nevertheless, it is unknown how the complex body shapes, draping of clothing, air gap and contact area (Psikuta et al. 2012; Frackiewicz-Kaczmarek et al. 2015) between the garment and the body impact sweat absorption values and patterns in clothing. In fact, wicking properties of clothing are not only determined by the amount of sweat produced at specific body locations, but can also be affected by the thickness of the air gap and the contact area between the garment and the human body (Psikuta et al. 2012; Frackiewicz-Kaczmarek et al. 2015). These parameters can be easily defined for a tight-fitting clothing item, as the sweat transfer between skin and such a garment would be expected to be similar to the body sweat pattern, given that these patterns were produced using absorbent material directly in contact with the skin (Havenith et al. 2008; Smith and Havenith 2011; Smith and Havenith 2012). Therefore, the aim of the current study was to provide detailed maps of sweat accumulation across a regular-fitting upper body garment, induced in male athletes during running exercise. The use of a regular-fitted garment, as most commonly used fit, allows determining the impact of clothing and personal factors on garment sweat absorption and migration.

Realistic sweat absorption data can support the development of garments with efficient moisture management features, e.g. with spatial variation of textile types. In terms of real-world impact, improvements in clothing moisture management can lead to improvements in heat loss efficiency as well as reductions in discomfort. A sensation of lower discomfort can boost people’s willingness to be physically active, thereby having a beneficial effect on health and well-being, along with improving performance and productivity of athletes and workers (Parsons 2014; DenHartog and Koerhuis 2017). Finally, the current findings can advance the existing knowledge on thermophysiological modelling.

7.2 Method

7.2.1 Participants

Eight male, long distance, runners were recruited from the Loughborough University student cohort (Table 1). The mean (± standard deviation) age was 23.3 ± 4.7 years and they were all of Western European origin. Their body mass, height and body fat was 70.0 ± 9.9 Kg, 177.3 ± 5.3 cm and 9.6 ± 4.5%, respectively. They were all training six times per week and the mean aerobic fitness level, measured as maximum oxygen uptake (VO_{2max}), was 62.0 ± 3.0· $mL{\cdot}kg^{-1}min^{-1}$. Immediately after the completion of the current study, four of the eight participants (P2, P3, P4, and P6), repeated the 10 experimental trials wearing a synthetic garment (sub-study). With regards to these four participants, the mean age was 20.3 ± 2.9 years. Their body mass, height and body fat was 66.8 ± 12.3 Kg, 175.6 ± 7.0 cm and 8.6 ± 3.7 %, respectively. Their VO_{2max} and running speed was 62.1 ± 3.7 $mL{\cdot}kg^{-}{}_{1}{\cdot}min^{-1}$ and 12.3 ± 0.6 $km{\cdot}h^{-1}$.

The experimental procedures where fully explained to the participants verbally and through written information form, before obtaining written informed consent and completing a health screening questionnaire. All the experimental procedures involved were approved by the Loughborough University Ethical Committee. The study was conducted within the confines of the World Medical Association Declaration of Helsinki for medical research involving human participants.

Table 1 Participants' characteristics.

Participant	Age (years)	Weight (Kg)	Height (cm)	BSA (m^2)	Body fat (%)	VO_{2max} ($mL \cdot Kg^{-1} \cdot min^{-1}$)	Running speed ($km \cdot h^{-1}$)
P1	19.0	66.3	177.0	1.8	7.2	64.0	11.8
P2	18.0	61.2	174.5	1.7	7.2	63.0	12.4
P3	21.0	55.4	168.0	1.6	6.5	62.0	11.4
P4	26.0	66.9	175.0	1.8	6.3	66.0	12.6
P5	33.0	69.0	177.0	1.9	5.5	63.0	11.6
P6	24.0	83.8	185.0	2.1	14.4	57.2	12.7
P7	22.0	82.0	183.0	2.0	12.3	57.5	11.0
P8	23.0	75.3	179.0	1.9	17.4	64.0	12.9
MEAN	23.3	70.0	177.3	1.9	9.6	62.1	12.1
STDEV	4.7	9.9	5.3	0.1	4.5	3.1	0.7

BSA = body surface area in m^{-2}. STDEV = standard deviation.

7.2.2 Pre-test

Participants were required to attend the laboratory for a pre-test, involving anthropometric measurements of height, body mass (Mettler Toledo Kcc150, Mettler Toledo, Leicester, UK), percentage of body fat (Tanita Corporation, Tokyo, Japan) and body dimensions.

During the pre-test participants also performed a sub-maximal fitness test to estimate their aerobic fitness level, expressed as maximal oxygen uptake (VO_{2max}). The sub-maximal fitness test was performed according to the American College of Sport Medicine guidelines for exercise testing and prescription (Thompson et al. 2010). The sub-maximal fitness test was conducted at an ambient temperature of 20 ^{o}C and 50 % relative humidity. The test comprises a series of running stages on a treadmill (h/p/cosmos mercury 4.0 h/p/cosmos sport & medical gmbh, Nussdorf-Traunstein, Germany). A system for the measurement of oxygen consumption (VO_2), including heart rate (HR) (COSMED Quark CPET Series, COSMED, Srl, Italy) was used. During the test the exercise intensity was progressively increased by changing the running speed by 2 km·h^{-1} every 4-min. The treadmill incline was not altered and maintained at 1% for the entire duration of the test. Each stage lasted 4-min to ensure a steady-state HR response. The end point of the test was determined when participants reached 85% of the individual age-predicted maximal HR (220 - age) (no more than 5 stages were performed). As long as work intensity is increased adequately (equal speed increment and duration of each stage) a linear relation can be observed between HR and VO_2 measured at the end of each running stage, and based on this relation, VO_{2max} was estimated from the age-predicted maximal HR. A similar linear relation can be observed between running speed and VO_2 at each running stage, and this was used to establish the corresponding speed for the testing (70% VO_{2max}).

7.2.3 Experimental conditions

Sweat absorption across the T-Shirt was mapped at 5-min intervals over a total running time of 50-min. As a 'destructive' gravimetric method was adopted to quantify regional sweat absorption, each participant performed 10 different running trials on a treadmill, characterised by different durations: 5 MIN, 10 MIN, 15 MIN, 20 MIN, 25 MIN, 30 MIN, 35 MIN, 40 MIN, 45 MIN and 50 MIN. In fact, immediately after each running trial, the T-Shirt was dissected into different parts (Fig 1) and each part was analysed to determine the time-course and distribution of sweat absorption over the duration of each run duration. In all the trials, the participants ran at the same individually fixed speed, corresponding to 70% of VO_{2max}; the mean running speed was 12.1 ± 0.7 $km \cdot h^{-1}$. The experiment was conducted in a small wind tunnel located in a climate-controlled chamber maintained at 27.2 ± 0.2 ^{o}C, 49.7 ± 3.2% RH and 1.5 $m \cdot s^{-1}$ wind speed. These specific environmental parameters were applied in order to allow direct comparisons with previous studies investigating body regional sweat rate patterns (Smith and Havenith 2011; Smith and Havenith 2012) .

7.2.4 .T-Shirt specifications

A fresh pre-washed (ISO 6330:2012), regular-fitted, short sleeved, T-Shirt was used for each of the 10 run durations. Sweat absorption and distribution was mapped in a 100% cotton garment, which, due to the higher hygroscopicity and greater capacity to retain liquid moisture, would represent the most challenging scenario for textile and clothing developers. The synthetic garment (100% polyester), included in the sub-study, was characterised by different thermal, evaporative and wicking properties from the cotton garment. The aim of this sub-investigation was to demonstrate that the properties of the fabric can affect sweat absorption values, rather than simply highlight differences between a natural and a synthetic garment. The synthetic garment was produced using the same fit pattern of the cotton garment. Material specifications of the cotton and synthetic garments are in Table 2.

Table 2 Specifications of the experimental garments

Garment	Mass ($g \cdot m^{-2}$)	Thickness (mm)	R_{ct} ($m^2 \cdot {}^{\circ}C/W$)	R_{ef} ($m^2 \cdot Pa/W$)	Air perm ($mm \cdot s^{-1}$)	Absorption ($g \cdot m^{-2}$)
100 % cotton	159	0.55	0.02	3.1	780	381
100 % polyester	127	0.46	0.01	2.2	2088	368

Rct = dry thermal resistance; Ref = water vapour resistance, Air perm = air permeability, Absorption = total absorption capacity. Dry thermal resistance and water vapour resistance were measured according to BS EN ISO 11092:2014, air permeability was measured according to BS EN ISO 9237:1995; total absorption capacity was measured according to the absorption capacity test adopted by Raccuglia et al.(2016), modified from Tang et al. (2014).

To better describe the fit design of the garment, here defined as 'regular', anterior and posterior picture of a participant wearing an experimental garment are provided in Figure 1.

In order to ensure same regular fit between participants presenting different body dimensions, three different T-Shirt sizes were included (Small, Medium and Large). The waist circumference of the participants was measured horizontally a level of the waist (where the smallest abdominal circumference occurs), while the person stands erect with the arms held slightly away from the side of the body. Three ranges of waist circumference were identified, small (68-73 cm), medium (74-79 cm) and large (80-85 cm). The circumference of each garment size, measured at the waist circumference of the participants, was taken. The latter was 90 cm for the Small size, 100 cm the Medium size, and 110 cm for the Large size, used for small (68-73 cm), medium (74-79 cm) and large (80-85 cm) waist circumference range, respectively.

Figure 1 Anterior and posterior picture of a participant wearing an experimental garment, here defined as regular-fitted.

Analyses of T-Shirt local sweat absorption (ABS_{local}) were conducted in 22 regions of the T-Shirt, 12 for the front and 10 for the back, respectively (Fig 2). The relevant sweat absorption zones within the T-Shirt were selected based on temperature patterns highlighted in infrared pictures (conducted in pilot testing), taken once the T-shirt was taken off (Fig 3). At the end of each run duration, analyses of local sweat absorption were conducted by cutting up the marked T-Shirt regions and weighing the individual sections before and after drying.

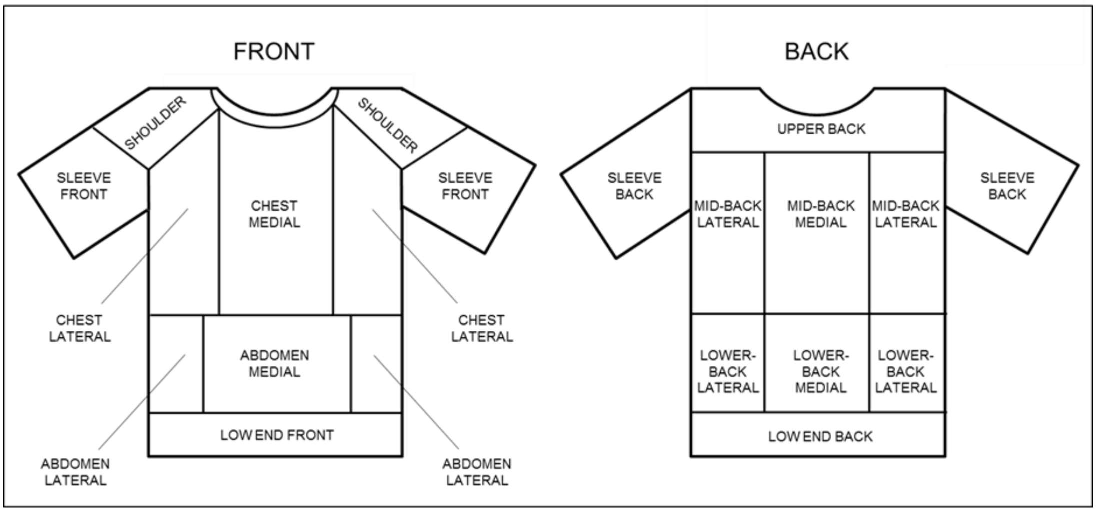

Figure 2 Schematic representation of the experimental T-Shirt marked into the 22 regions of interest for the analyses of local sweat accumulation. Front and back of the T-Shirt were mapped into 12 and 10 zones, respectively.

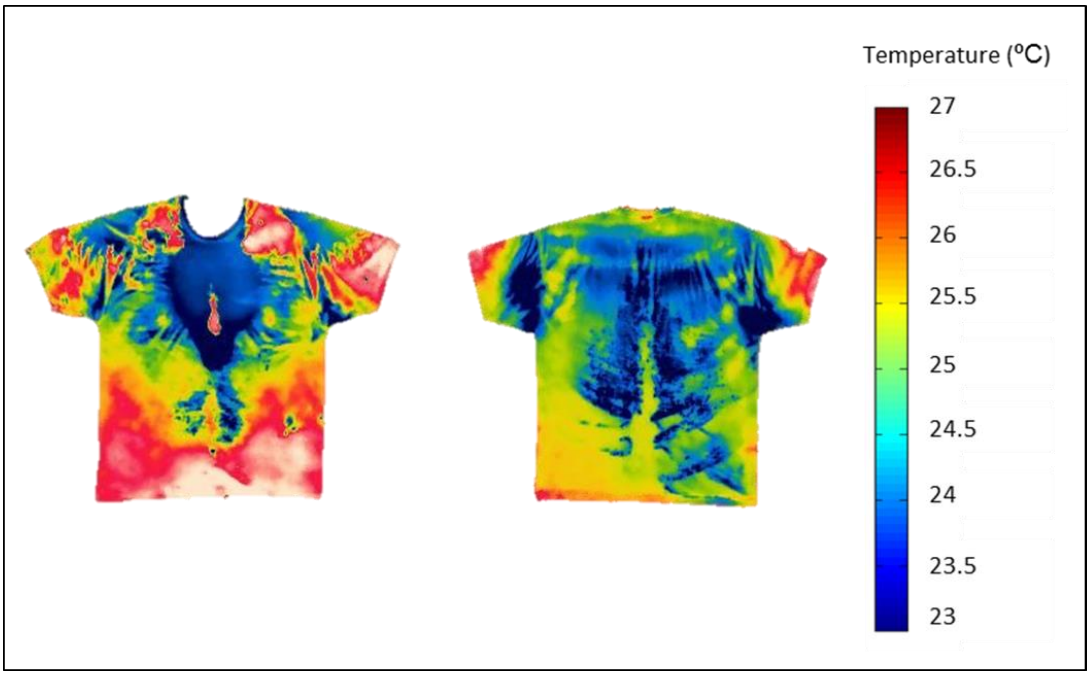

Figure 3 Infrared pictures of front and back of the T-Shirt taken to identify variations in sweat retentions between various T-Shirt regions.

7.2.5 Experimental protocol

Participants performed the 10 running trials on different days, separated by at least 24 hours of rest. The testing sequence was counterbalanced to prevent any order effect. Each participant performed the trials at the same time of the day to minimise circadian variation. Participants were instructed to refrain from strenuous exercise, abstain from caffeine and alcohol consumption 24 hours before testing, and to keep a record of their food intake and replicate it the day before each visit. In order to maintain euhydration, they were also advised to consume 20 $mL \cdot Kg^{-1}$ body weight of water during the two hours prior to testing. On arrival to the laboratory participants were asked to void their bladders, self-insert a rectal probe, for the measurement of core body temperature, and wear a wrist-based HR monitor. Following from this, semi-nude (including underwear, rectal probe and HR monitor) body mass was recorded. Subsequently, participants were provided with standard running shorts and socks, wore their personal running shoes. Participants were asked to use the same personal running gears for the entire duration of the experiment. This period of preparation lasted approximately 15-min and allowed time for the stabilisation of HR and T_{core}. Participants moved to the climate-controlled room, rested standing still on the treadmill and after 10-min baseline HR was recorded. They then worn the experimental T-Shirt and the running trial started. In order to prevent dehydration, the participants were allowed to drink water *ad libitum* during the experiment, and liquid consumption was recorded. At the end of the run participants took the worn T-Shirt off which was given to the experimenter for measurements of local sweat absorption. The participants took shorts, sock and shoes, towelled their skin (this took ~ 2-min) and post-exercise semi-nude body mass was recorded immediately.

7.2.6 Measurements

7.2.6.1 Physiological measurements

Heart rate was recorded before (baseline, BL) and during the running trials at 1-min intervals with a wrist-based heart rate monitor (Polar A360, Polar Electro Oy, Professorintie 5, Kempele, Finland). A wrist-based monitor, rather than a chest-based monitor, was used since a chest strap would have interfered with sweat transfer from the skin to the T-Shirt. To monitor changes in $T_{core,}$ rectal temperature was recorded via a rectal thermistor (Grant Instrument Ltd, Cambridge, UK), inserted 10 cm beyond the anal sphincter. Rectal temperature was measured throughout each experimental trial at 1-min intervals and recorded via a portable data logger (Grant Instrument Ltd, Cambridge, UK) connected to the thermistor's probe. Sweat production was calculated based on the weight change of each participant (gross sweat loss, GSL), corrected for liquid intake, and reported in grams per body surface area ($g \cdot m^{-2}$), according to:

$$GSL\ (g \cdot m^{-2}) = [w_{b1} - (w_{b2} - liquid)]/SA$$

Where;

w_{b1} body mass at the start of the experiment (g)

w_{b2} body mass at the end of the experiment (g)

liquid total water consumption (g)

SA body surface area (m^2)

7.2.6.2 Total and local T-Shirt sweat content

Extensive pilot testing was conducted in order to define the exact locations and the number of zones to map within the T-Shirt. Two participants conducted a full set of pilot trials and at the end of each pilot test infrared picture of the T-Shirt were taken to identify variations in sweat absorption between regions and over time. The infrared pictures permitted to visually detect, based on colour differences, T-Shirt regions characterised by diverse temperatures. It was assumed that variations in temperature across the T-Shirt corresponded to variations in sweat content, and based on this principle, the T-Shirt was mapped in 22 different zones: 12 for the front and 10 for the back (Fig 2). To the knowledge of the authors, currently there are no standardised methods able to directly and accurately measure liquid moisture content in specific clothing sections, without dissecting the garment. A gravimetric method, based on weight changes (difference between wet and dry garment weight) is typically adopted to estimate sweat absorption in a full garment. However, since each individual section of the T-Shirt to be measured could not be weighed prior testing, it was decided to adopt a 'destructive' gravimetric method, in which each T-Shirt region was cut up immediately following sweat collection, and based on weight changes local sweat content was estimated. Twelve hours before being worn, the T-Shirt was marked with a permanent pen into the 22 sections and left in a climate-controlled room (20 ºC, 60% relative humidity). Immediately after being taken off, the T-Shirt was fitted to a T-Shirt-shape wooden stand and divided into front and back panel, to prevent sweat transfer from the front to the back and vice versa. Front and back of the T-Shirt were separately laid flat on a table and each pre-marked section was cut up. The order of cutting was balanced to prevent any order-related error. It took a maximum of 7-min to cut up the full T-Shirt, as it was assessed in a pilot test that after 7 min, the weight of the full T-Shirt starts to change due to drying. Immediately after being cut, the specific T-Shirt regions were placed in individually labelled airtight bags, to prevent sweat evaporation. The weight of each wet T-Shirt section inserted into the corresponding bag was recorded using a calibrated electronic weighing scale (PSK 360-3, Kern,UK), with a maximum load of 360 g and a precision of 0.001 g. After being cut, the sections were then taken off the bag and placed in a chamber at 30 ºC and 7 % relative humidity for 12 hours, to allow the material to dry. The dried sections where then re-weighted without the bags to establish the dry weight. Local sweat absorption (ABS_{local}) was calculated from the weight change and the surface area of each section according to:

$$ABS_{local}\ (g \cdot m^{-2}) = [(w_{wet} - bag) - w_{dry}]/SA$$

Where;

w_{wet} section wet weight, including bag (g)

w_{dry} section dry weight (g)

bag mass of the airtight bag (g)

SA section surface area (m^2)

To calculate the SA of each T-Shirt section, 5 control samples of the T-Shirt's fabric were produced and the dry weight per unit area ($g \cdot m^{-2}$) was calculated from size and weight of each control sample according to:

$$ASW\ (g \cdot m^{-2}) = (w_c / a_c) \cdot 10000$$

Where;

ASW Area specific weight

w_c weight of control material (g)

a_c area of control material (cm^2)

The area weight of the control samples was stable, showing only 1.3 % coefficient of variation. The mean value of the calculated weight per unit area of the 5 control samples was used in the calculation of each T-Shirt section SA in $g \cdot m^{-2}$ according to:

$$SA = w_d / ASW$$

Where;

w_d dry weight of material (g)

Since weight measurements of the wet full T-Shirt after the sweat collection period could have caused sweat transfer through contact between T-Shirts regions, ABS_{total} was calculated from the sum of ABS_{local}, according to:

$$ABS_{total} = (\sum ABS_{local})$$

Where;

ABS_{local} sweat accumulated in a specific T-Shirt region (g)

7.3 Statistical analysis

Differences in HR and T_{core} recorded at same time points in different run durations were assessed with paired t-test (2 comparisons) and one-way repeated measures ANOVA (more than 2 comparisons). HR and T_{core} data were averaged across same time points, and one single mean value per time point is reported and displayed in the figures.

One-way repeated measures ANOVA tests were performed to assess differences in and HR, T_{core}, GSL and ABS_{total} between run durations. When statistical differences were observed post hoc tests with Bonferroni correction for multiple comparisons were conducted. As the progressive development of GSL and ABS_{total} was measured in different trials, the data were combined and reported over time.

Local sweat absorption data (ABS_{local}) were firstly analysed to assess differences in corresponding right-left zones (shoulders, sleeves front, sleeves back, chest lateral, abdomen lateral, lateral mid-back, lateral lower-back). Paired t-tests were performed for all the right-left zones with Bonferroni correction for multiple comparisons. To assess differences between local sweat absorption data, one-way repeated measures ANOVA tests were conducted. The large number of comparisons between zones can cause inflation of the type I error; nevertheless the application of Bonferroni correction to adjust for multiple comparisons can inflate the type II error. Therefore, it was decided to report both corrected an uncorrected p values, keeping in mind the exploratory nature of the research, yet recognising the conservative nature of Bonferroni correction (Smith and Havenith 2012) (Supplemental digital content).

Descriptive statistics reporting, min and max values, median, mean and standard deviation in ABS_{local} for each region was conducted. Linear regression analyses were performed to observe relations between variables, in particular between ABS_{total} and GSL. In all analyses, $p < 0.05$ was used to establish significant differences. Data are reported as mean (standard deviation (SD)). Statistical analysis was performed using the software IBM SPSS Statistics version 23 (IBM, Chicago, USA).

7.4 Results

There were no evident differences between the cotton and synthetic conditions in physiological data of T_{core}, HR and GSL, obtained from the four participants taking part in both conditions. The following results refer to physiological data achieved in the experiment involving the use of the cotton garment.

7.4.1 Heart rate and core temperature

Heart rate (HR) and core temperature (T_{core}) were measured at 1-min intervals throughout each running trial. Both HR and T_{core} were not significantly different ($p > 0.05$) at same time points and between trials, therefore data were averaged across the 10 run durations. HR and T_{core} both increased significantly during exercise ($p < 0.001$). Baseline HR was 69 ± 15 bpm and increased up to 163 ± 17 bpm at the end of the 50 MIN run duration, while T_{core} rose from 37.0 ± 0.17 ^{o}C , at baseline, to 38.6 ± 0.28 ^{o}C at the end of the 50 MIN (Fig 4).

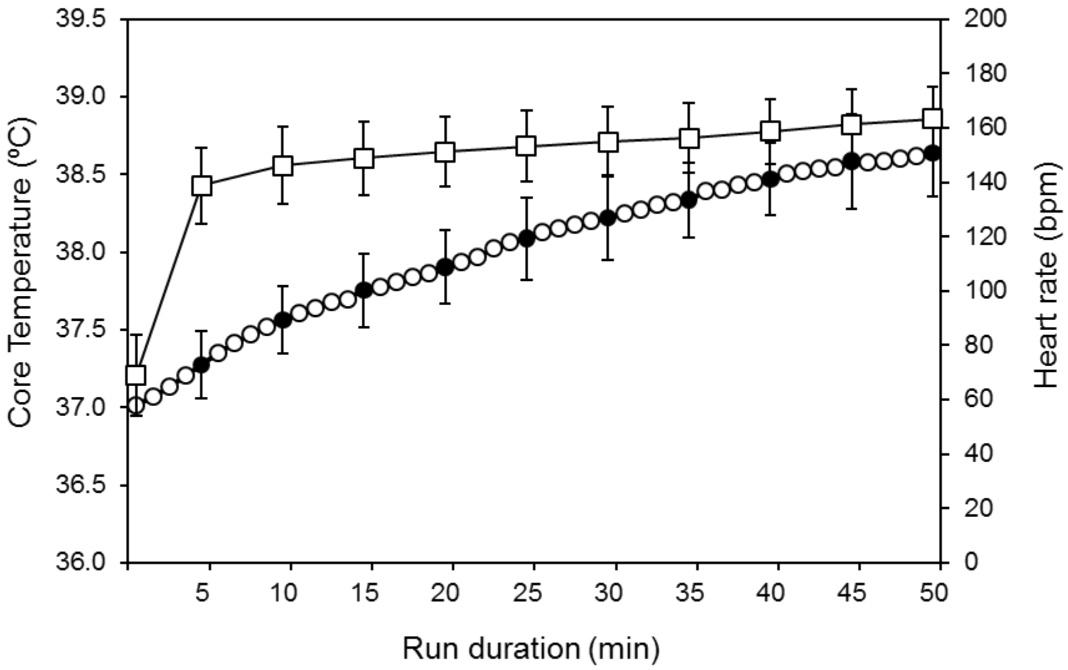

Figure 4 Mean core temperature (T_{core}; circle symbols) and mean heart rate (HR; square symbols) data for 8 male athletes. Data were averaged over the 10 run durations (from 5 MIN to 50 MIN). T_{core} and HR values were sampled at 1-min intervals. The average over 5 min is presented for HR measurements. Data are presented as mean (SD).

7.4.2 Gross sweat loss

Substantial variation in the amount of whole body produced sweat, measured as gross sweat loss (GSL), was observed between individuals (Fig 5-A). GSL, was corrected for the individual body surface area ($g \cdot m^{-2}$). Cumulative GSL linearly increased as function of run duration: at 5 MIN run it was 48 ± 13 $g \cdot m^{-2}$ and the highest value was 586 ± 85 $g \cdot m^{-2}$ observed at 50 MIN (Fig 5-A). The mean rate of GSL increase was 11.0 ± 0.4 $g \cdot m^{-2} \cdot min^{-1}$.

The ANOVA test showed significant differences ($p < 0.001$) in GSL between run durations; however when the Bonferroni correction for multiple comparison was applied, the differences were not significant ($p > 0.05$) between 30 MIN and 35 MIN neither between 35 MIN and 40 MIN.

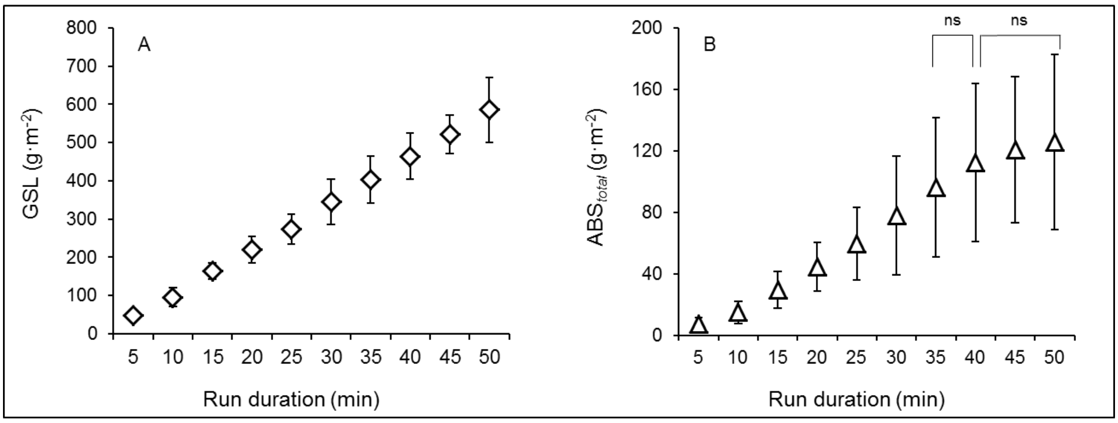

Figure 5 Gross sweat loss (GSL) data (Panel A) and T-Shirt total sweat absorption (ABS_{total}) data (Panel B). The mean (SD) values for 8 male athletes are presented. GSL and ABS_{total} data for each time point were obtained from 10 different run durations. GSL was significantly different between the 10 run durations. ABS_{total} was significantly different between the run durations but the differences were not significant (ns) between 35 MIN - 40 MIN and 40 MIN - 45 MIN - 50MIN.

7.4.3 Total and local T-Shirt sweat absorption

Both total T-Shirt sweat absorption (ABS_{total}) and ABS_{local} data between run durations were corrected for fabric surface area and reported as $g \cdot m^{-2}$. Considerable variation in ABS_{total} was observed between individuals (Fig 5-B). ABS_{total} was greatly influenced by the large variation in GSL, indicated by a linear positive relation between ABS_{total} and GSL ($r^2 = 0.74$, $p < 0.001$). ABS_{total} increased with the increase in run duration. The highest mean ABS_{total} value was

126 ± 57 g·m^{-2} observed in the 50 MIN run and the mean rate of increase was 3.5 ± 0.8 g·m^{-2}·min^{-1}. At the end of the 50 MIN run the T-Shirt was 41% saturated, calculated as percentage of total T-Shirt absorption capacity (305.5 g). This also means that, after 50 MIN run, 9.3% of the whole body produced sweat was collected and retained by the T-Shirt (this when using absolute mean values of GSL and ABS_{total}, 1083 g and 101 g, respectively).

The ANOVA test showed significant differences ($p < 0.001$) in ABS_{total} between run durations; however the differences were not significant ($p > 0.05$) between 35 MIN and 40 MIN neither between 40 MIN, 45MIN and 50 MIN.

Right and left corresponding T-Shirt regions (shoulders, front sleeves, back sleeves, lateral chest, later abdomen, lateral mid-back, lateral lower-back) did not show significant differences ($p > 0.05$) in ABS_{local} and thus left-right data were grouped for all analyses. For practical reasons, descriptive statistics for all the regions are reported only for 10 MIN, 20 MIN 30 MIN, 40 MIN and 50 MIN run durations (Table 2).

Mean ABS_{local} data for front and back of the T-Shirt, from 5 MIN to 50 MIN, are presented in Fig 6. Additionally, comparisons between T-Shirt regions within each run condition were conducted, (Extended data set).

Local T-Shirt saturation was also calculated as percentage of the total absorption capacity of the material (g·m^{-2}). At the end of the 50 MIN, medial mid-back and medial lower-back were the most saturated T-Shirt parts: 56% and 51%, respectively. These were followed by upper back, collar and chest medial (40-45%), and next to these, lateral mid-back, lateral chest and lateral abdomen reached between 30 and 39% of the saturation. Shoulders, sleeves front and back and lateral lower-back were 20-29% saturated and the lowest saturation level was shown by front and back low ends together with lateral abdomen (7-12 %).

A clear large variation in ABS_{local} between participants was evident from the minimum and maximum value and standard deviation data within each region (Table 3). For most of the regions mean and median values were very close, indicating normal distributions. When large differences occur, usually the mean is higher than the median, normally due to a one or two ‘high sweaters’ in the group(Havenith et al. 2008; Smith and Havenith 2011; Smith and Havenith 2012).

The coefficient of variation (CV %) in ABS_{local} between participants was calculated, to compare the variation in ABS_{local} between T-Shirt regions. To achieve an overall identification of the regions with ‘higher’ and ‘lower’ variation, CV data for each region of interest were averaged over run durations. Differences in CV were observed, with hem at the back showing the highest value (99 %) and the upper back the lowest (44%). The variation was higher in the inferior T-Shirt regions compared to the superior ones and in the peripheral parts as compared to the central regions. When using ABS_{local} values normalised for whole individual body sweat production (ABS_{local} / GSL), the CV in ABS_{local} appears to be lower (~ 6%) for all the T-Shirt regions compared to the CV values obtained when using absolute data. Nevertheless, the pattern of ABS_{local} variation across T-Shirt regions is similar between absolute and normalised data.

7.4.4 Sub-study: synthetic garment

Baseline HR was 66 ± 12 bpm and increased up to 163 ± 17 bpm at the end of the 50 MIN run duration, while T_{core} rose from 37.0 ± 0.13 ºC , at baseline, to 38.6 ± 0.46 ºC at the end of the 50 MIN. ABS_{total} in the synthetic garment increased with the increase in run duration. The highest mean ABS_{total} value was 51.4 ± 27.5 $g{\cdot}m^{-2}$ observed in the 50 MIN run. At the end of the 50 MIN run the T-Shirt was 17.5% saturated. Mean ABS_{local} data for front and back of the T-Shirt, from 5 MIN to 50 MIN, are presented in Figure 7. Descriptive statistics for all the regions are reported only for 10 MIN, 20 MIN 30 MIN, 40 MIN and 50 MIN run durations is reported in Table 4.

Table 3 Descriptive statistics of sweat absorption data for all the T-Shirt regions of interest.

	area	10 MIN					20 MIN					30 MIN					40 MIN					50 MIN				
	m2	min	max	median	mean	SD	min	max	median	mean	SD	min	max	median	mean	SD	min	max	median	mean	SD	min	max	median	mean	SD
Collar	0.017	0	133	14	40	49	33	208	113	115	68	28	239	129	146	79	53	251	176	177	67	53	318	174	171	93
Shoulders	0.032	2	25	8	10	7	15	52	27	29	14	21	102	42	50	30	35	148	108	95	41	32	173	104	103	58
Sleeves front	0.030	5	20	9	10	5	5	48	18	21	13	14	61	21	31	19	7	89	32	43	28	13	133	41	57	44
Chest medial	0.053	7	57	11	18	18	19	206	75	101	72	25	258	135	139	92	55	250	191	172	82	44	245	203	171	83
Chest lateral	0.040	5	15	9	9	4	6	83	15	31	28	17	132	37	55	46	17	200	106	106	79	26	242	105	115	82
Abdomen medial	0.043	4	21	10	10	5	6	52	17	23	17	9	258	24	68	90	6	257	115	122	106	7	275	97	117	104
Abdomen lateral	0.029	1	7	6	5	2	5	13	10	9	2	5	60	11	16	18	4	77	17	26	26	4	207	13	45	70
Low end front	0.062	0	9	5	5	2	4	99	6	17	33	5	10	7	7	1	3	12	5	7	3	4	62	23	24	20
Upper back	0.067	0	53	16	23	20	44	121	78	75	27	70	222	124	128	58	120	231	166	174	44	64	228	178	162	59
Sleeve back	0.037	7	35	19	19	9	15	69	43	41	16	31	122	55	66	30	38	138	76	89	40	51	195	89	102	47
Medial mid-back	0.048	10	87	23	35	29	46	184	125	124	40	69	265	195	181	78	119	271	223	209	52	134	271	230	215	50
Lateral mid-back	0.043	10	34	15	18	8	18	82	46	52	26	27	172	103	98	52	51	236	132	142	71	51	254	163	161	72
Medial lower-back	0.036	7	62	16	22	18	19	156	51	65	42	8	89	29	44	33	88	277	168	177	70	117	290	187	198	63
Lateral lower-back	0.032	1	23	8	9	7	8	51	23	23	14	8	89	29	44	33	9	200	54	77	68	18	235	66	94	86
Low end back	0.061	2	7	5	5	1	3	10	6	6	2	6	12	9	9	2	4	123	7	23	41	3	243	9	49	82

T-Shirt local sweat absorption data of 8 male athletes are reported for 10 MIN, 20 MIN 30 MIN, 40 MIN and 50 MIN run durations. Minimum (MIN) and maximum (MAX) values, along with median, mean and standard deviation (SD), are reported for each region of interest.

Table 4 Descriptive statistics of sweat absorption data for all the T-Shirt (*synthetic*) regions of interest.

	area	10 MIN					20 MIN					30 MIN					40 MIN					50 MIN				
	m2	min	max	median	mean	SD	min	max	median	mean	SD	min	max	median	mean	SD	min	max	median	mean	SD	min	max	median	mean	SD
Collar	0.017	3	13	8	8	5	13	133	35	60	64	13	144	75	77	65	42	157	90	96	58	36	152	97	95	58
Shoulders	0.032	0	11	3	5	6	1	22	2	9	12	0	43	4	16	24	12	60	50	41	25	11	73	28	38	32
Sleeves front	0.030	0	14	9	7	7	7	21	8	12	8	3	20	6	10	9	6	35	17	20	15	2	52	17	24	26
Chest medial	0.053	1	7	5	4	3	9	99	20	42	50	6	105	37	49	51	17	141	58	72	63	17	134	72	74	59
Chest lateral	0.040	0	12	6	6	6	1	36	6	14	19	1	42	2	15	23	4	99	13	39	52	12	111	13	45	57
Abdomen medial	0.043	0	17	3	7	9	0	6	3	3	3	0	2	1	1	1	4	99	6	36	54	3	147	6	52	82
Abdomen lateral	0.029	0	10	0	3	6	0	3	1	1	1	2	14	10	9	6	0	45	2	16	25	0	61	8	23	33
Low end front	0.062	0	5	3	3	3	0	3	1	1	1	0	2	1	1	1	0	3	3	2	2	0	33	3	12	18
Upper back	0.067	0	14	7	7	7	30	52	33	38	12	39	64	56	53	12	61	101	84	82	20	80	117	91	96	19
Sleeve back	0.037	3	24	17	15	11	9	33	22	21	12	14	39	17	23	13	24	53	41	39	15	20	58	51	43	20
Medial mid-back	0.048	0	20	7	9	0	36	73	40	50	0	24	104	39	56	0	49	115	95	86	0	69	124	118	104	0
Lateral mid-back	0.043	0	15	11	8	7	5	24	12	14	9	8	55	15	26	26	20	76	42	46	28	20	87	69	58	35
Medial lower-back	0.036	0	5	4	3	3	13	19	14	15	3	5	41	9	18	20	21	70	44	45	25	29	91	73	64	32
Lateral lower-back	0.032	1	11	3	5	6	0	9	1	3	5	1	13	7	7	6	12	33	17	21	11	0	35	20	18	17
Low end back	0.061	0	0	0	0	0	0	10	0	3	6	0	2	1	1	1	0	0	0	0	0	0	70	0	23	40

T-Shirt local sweat absorption data of 4 male athletes are reported for 10 MIN, 20 MIN 30 MIN, 40 MIN and 50 MIN run durations. Minimum (MIN) and maximum (MAX) values, along with median, mean and standard deviation (SD), are reported for each region of interest.

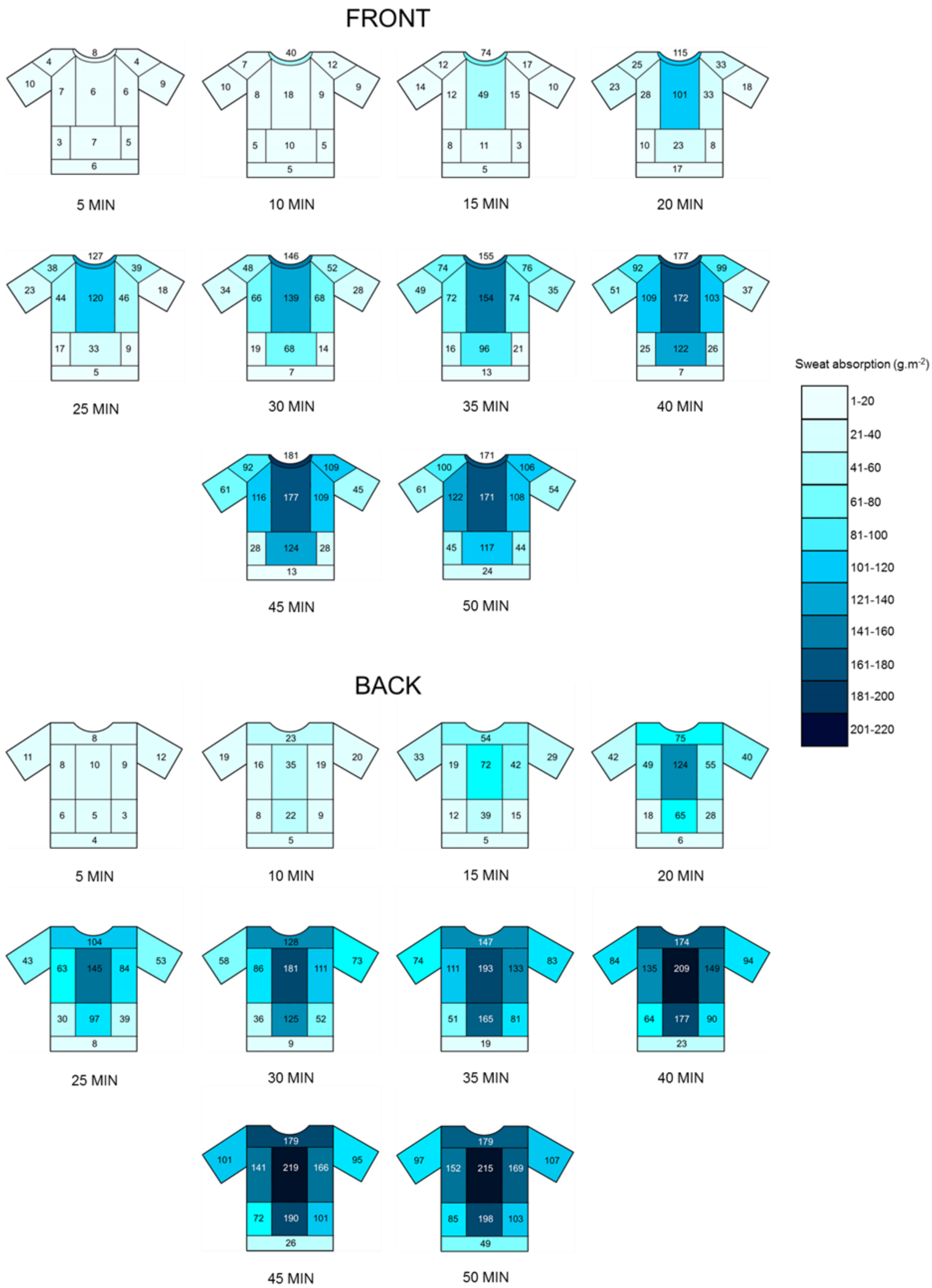

Figure 6 Mean T-Shirt (*cotton*) local sweat absorption data for 8 male athletes. Local sweat absorption was measured at 5-min intervals from 5 min to 50 min of running exercise, for front and back T-Shirt zones. Data were obtained from 10 different run durations.

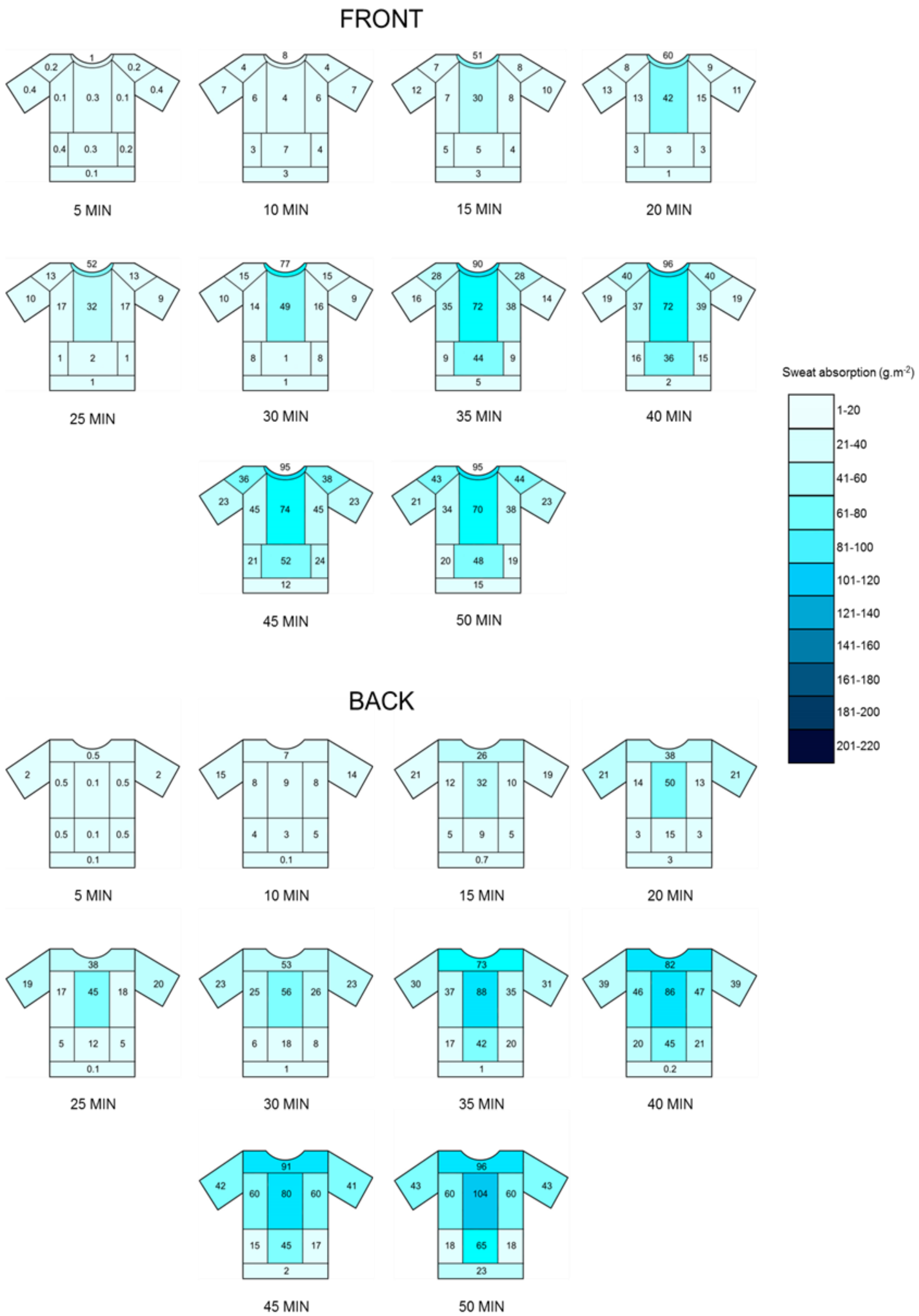

Figure 7 Mean T-Shirt (*synthetic*) local sweat absorption data for 4 male athletes. Local sweat absorption was measured at 5-min intervals from 5 min to 50 min of running exercise, for front and back T-Shirt zones. Data were obtained from 10 different run durations.

7.5 Discussion

The present investigation aimed to study the migration of sweat from the skin to clothing, specifically in cotton and synthetic upper body garments, over 50 minutes of running exercise performed by male athletes. Based on the obtained values, a series of maps of sweat absorption in such garments were created. The study provided quantitative data on total as well as regional sweat absorption in the studied garments and clearly demonstrated considerable variation between different garment zones.

A large part of the individual variation in the total amount of sweat absorbed by the T-Shirt was due to the large individual variation in whole body sweat production. In fact, although in the current study it was not possible to simultaneously measure the amount of sweat solely produced in the body parts covered by the T-Shirts, using individual GSL as covariant resulted in a 6% lower variance between individuals. T-Shirt absorption increases significantly with exercise duration, but starts to plateau after 35 minutes, although this was not accompanied by maximal T-Shirt moisture saturation. In fact, after 50 minutes of running exercise, the cotton and synthetic garments reached, on average, only 41% and 18% of the total absorption capacity, respectively. The highest local moisture saturation was achieved in the mid-medial back and it was around 56% and 35 % in the cotton and synthetic garment, respectively.

From the early stages of the running activity (after 15 minutes) a clear pattern in local sweat accumulation was observed. The maps in Figure 6 and 7 highlight a decrease in sweat content from medial to lateral and from the top to the bottom, both for front and back of the T-Shirt. These patterns were maintained throughout the rest of the running exercise (35-50 minutes).

The inter-regional differences in T-Shirt sweat accumulation can be explained by the interactions of physiological, anatomical and clothing factors. When wearing a T-Shirt with a regular fit, the top parts, covering chest as well as upper and mid back, are directly in contact with the body, due to the absence of an air gap. Consequently, these upper T-Shirt parts will be directly and constantly in contact with the skin, this facilitating sweat absorption. In addition to this, regional sweat rate distribution, in male runners (Smith and Havenith 2012), shows a consistent pattern of sweat rate reduction from high to low body regions, with the posterior torso, especially at the spine, having the highest values. Therefore the combination of clothing factors, i.e. high fabric-to skin contact and physiological factors, i.e. high sweat rate, explains the highest sweat accumulation in the top-posterior and top-anterior regions of the T-Shirt. Specifically, the medial-upper portion of the T-Shirt, in contact with mid-back, upper back and medial chest, showed the highest sweat accumulation.

On the other hand, the bottom parts of a T-Shirt (presenting a regular fit) typically hang loose in those regions covering lower back and abdomen, due to specific body shapes (i.e. lumbar curvature) and draping behaviour of clothing. This is likely to result in a relatively large air gap between the T-Shirt and the body (Psikuta et al. 2012; Frackiewicz-Kaczmarek et al. 2015), causing a less direct and only intermittent T-Shirt-to-skin contact, mainly occurring from air and body movement. This will hamper garment sweat absorption, despite a physiologically high sweat rate at the lower back (Smith and Havenith 2012). In line with this, it can be observed, from the current T-Shirt sweat maps that in the bottom posterior parts of the T-Shirts sweat accumulation is substantially lower or appears later compared to the top ones, in both cotton and synthetic garments. In particular, the lower-posterior portion of the T-Shirt, covering the lower back, starts to show a substantially high sweat content, only after 35 min minutes. Therefore, it can be speculated that most of the sweat accumulated in the low-posterior part of the T-Shirt is the result of sweat migration from the top to the bottom T-Shirt regions, whereas in these inferior zones the high local sweat rate (Smith and Havenith 2011; Smith and Havenith 2012) plays a minor role. The same principle applies for the bottom-anterior parts of the T-Shirt, covering the abdomen. In fact, the latter regions present a small contact area with the skin and some of these are mostly in contact with the shorts. Additionally, lower abdominal regions present a substantially lower sweat rate, compared to the back (Smith and Havenith 2011; Smith and Havenith 2012). This may explain the significantly lower sweat content in the T-Shirt regions covering the abdomen, in particular the lateral abdomen and the lower hem of the T-shirt at the front, but also at the back. Finally, the low sweat accumulation, being dependent mostly on sweat migration from the superior T-Shirt parts, may also contribute to the larger variations in sweat content in the inferior compared to the superior T-Shirt zones.

In line with regional sweat rate data in males (Smith and Havenith 2011), T-Shirt sweat accumulation values tend to be higher at the posterior compared to the anterior part of the T-Shirt. Overall, local sweat absorption patterns reflect body regional sweat rate as determined by Smith et al. (2011; 2012), although, as expected, values are substantially lower in absolute terms. Body sweat maps were produced with the aim of quantifying regional differences in sweat rate across the body. In these studies, a highly absorbent material was placed directly in contact with the skin, for a 5 min period, to allow collection of local body sweat and the absorbed material was covered by an impermeable film to prevent sweat evaporation during the collection period. In the current study, the sweat produced in the upper body could evaporate or be ventilated directly from the skin but also from the T-Shirt. Moreover, to simulate real life conditions, sweat from the head, forehead, and face was allowed to drip on the garment. As such, the combination of these factors is represented in the data, reflecting realistic wear conditions occurring during exercise.

With regards to thermal, evaporative and moisture properties of textile materials, it can be confirmed that these substantially impact the absolute amount of total as well as local sweat absorbed in the garment. In fact, as expected, sweat absorption data were substantially lower in the synthetic garment as compared to the cotton garment; nevertheless, the patterns of sweat distribution appeared to be very similar (Fig 6 and Fig 7). These findings nicely demonstrate that differences in textile properties can determine the absolute amount of sweat absorbed and distributed across the garment, thereby affecting post-exercise body cooling provided, this being approximately 255 W and 104 W in the cotton and synthetic garment, respectively (assuming a post exercise-time of 20 minutes and when sweat evaporation occurs from the skin (Havenith et al. 2013). On the other hand, garment fit mainly affects the patterns of sweat absorption distribution in clothing, through its effect on fabric-to-skin contact and air gap thickness. Together with textile properties, environmental factors, such as relative humidity, temperature and air flow, could also influence absolute sweat absorption data.

7.6 Conclusions

This study provided data on sweat accumulation in cotton and synthetic garments occurring during exercise performed by male runners. A clear pattern of sweat absorption reduction from the top to the bottom and from the centre to the sides of the T-shirt was observed in both cotton and synthetic garments. The study reaches conclusions of interest to an interdisciplinary readership. The current results represent useful guidelines for clothing developers when designing products with efficient moisture management features. Given that the sides of the T-Shirt contain a significantly lower amount of sweat compared to the central parts, innovative fibre and textile structures should be placed to direct sweat migration from the centre towards the less saturated side regions. The latter would improve sweat management and evaporation, ultimately reducing thermal and sensorial discomfort during exercise as well as heat strain. Thus, the use of the current sweat absorption data is recommended to clothing developers and textile engineers for the development of materials and clothing that can fulfil real life user's requirements. These data can also be applied as reference values for test methods and apparatus that measure fabric and clothing moisture-related properties. Knowing how much sweat ends up in the garment, at a specific garment region and at a set running time, can help to realistically measure critical parameters like drying rate/time, thus allowing predictions of comfort-related and thermophysiological responses or in extreme scenarios, estimations of survival time. Finally, the large variation in total and local sweat absorption data is a clear sign that clothing customization is required in order to suit individual body sweat responses. In fact, the design of a single T-Shirt, based on mean sweat absorption data may not accommodate the needs of athletes or consumers with extremely low or high sweating responses. A step forward will involve women athletes to create maps of sweat absorption in a bra-T-Shirt clothing system.

CHAPTER 8

Laboratory study 6

The use of infrared thermal imaging to measure spatial and temporal sweat retention in clothing

CHAPTER SUMMARY

In Study 5 a 'destructive' gravimetric method was developed to quantify local garment sweat absorption. While this currently is the only methodology that permits direct and analytical measurements of garment regional sweat absorption, the latter approach is time-consuming and expensive, therefore of limited applicability. As such, in this study, we wanted to assess whether infrared thermography could be used as an indirect method to estimate garment regional sweat absorption, right after exercise, in a 'non-destructive' fashion. Spatial and temporal sweat absorption data, obtained from Study 5, were correlated with spatial and temporal temperature data (also obtained from study 5) measured with an infrared thermal camera. The data suggest that infrared thermography is a good tool to predict regional sweat absorption in garments at separate individual time points; however temporal changes are not predicted well, due to a moisture threshold causing a temperature limit above which variations in sweat content cannot be discriminated by temperature changes.

8.1 Introduction

Temperature and moisture management in clothing is a main focus of the clothing industry with regards to garment performance optimisation and wear discomfort reduction. Liquid moisture content and transfer properties of fabrics can be assessed with a range of material test methods. In these tests, physical wetness of fabrics is induced by the investigator and/or specific apparatus, by adding water or special solutions. Moisture properties of fabrics are then measured via the application of different technologies, e.g. gravimetric, observation, optical, electrical and temperature-based methods (Tang et al. 2014b). Although these tests are quick, easy and relatively cost-effective, they do not fully simulate the conditions in which liquid moisture absorption and transfer occur, such as in the clothed human body during physical work. In real life use, immediately after physical exercise, a gravimetric method, based on weight changes (difference between wet and dry garment weight) is typically adopted to estimate sweat absorption in a full garment (Baker et al. 2017). Nevertheless, to the knowledge of the authors, there are no standardised test methods able to directly measure liquid moisture content in specific clothing sections, without dissecting the garment. In our previous study (Study 5), a 'destructive' gravimetric method was developed to quantify garment regional sweat absorption. In this test, each T-Shirt region was cut into sections immediately following sweat collection and based on weight changes local sweat content of each section of the garment was then estimated. While this currently is the only methodology that permits direct and analytical measurements of garment regional sweat absorption, the latter approach is time-consuming and expensive, therefore of limited applicability.

In the building industry infrared thermography (IRT) is used as diagnostic tool to detect the presence of damp in the cavity of walls and floors or the deterioration of historic structures due to moisture infiltration (Balaras and Argiriou 2002; Avdelidis et al. 2003). IRT involves the use of an infrared camera which can detect thermal radiation and produce colour images, termed as thermograms (Ring and Ammer 2000). A thermogram contains temperature data and one of the main advantages is that it allows us to visualise temperature differences across the object captured, using colour differences that are related to a colour-temperature scale. Taking a cue from the building industry, given that textiles also cool when water (sweat) is present, we wanted to assess whether IRT could be applied to detect liquid moisture content in clothing and, more importantly, quantify spatial variation in this liquid content across the garment.

The improved sensitivity of infrared cameras (approximately 0.05 ^{o}C) allows detections of small temperature differences across objects examined, which is of crucial importance when adopting a temperature mapping approach (Fournet et al. 2013; Gerrett et al. 2015). The method is non-invasive, non-destructive and does not requires contact with the object examined (Formenti et al. 2016). The acquisition of the infrared images is quick and easy to perform, however various protocols, guidelines and checklist must be followed (IACT 2002; ISO 9886:2004; Ammer 2008; Mercer and Ring 2009; Moreira et al. 2017) in order to prevent bias and obtain good quality data. For instance, attention should be paid to the position of the camera, distance of the camera from the object captured, operating and object temperature ranges as well as additional sources of calibration (mainly due to the absolute low accuracy, ± 2 ^{o}C).

As a result of the numerous advantages, IRT has been used for a number of different applications (Moreira et al. 2017), including sport-related injuries prevention and treatment (Hadžić et al. 2015), activation of brown adipose tissue in the body (Robinson et al. 2016), assessments of cryotherapy protocols (Costello et al. 2012; Selfe et al. 2014; Silva et al. 2017) and measurements of skin temperature following aerobic and resistance exercise (Ferreira et al. 2008; Priego Quesada et al. 2015). Furthermore, IRT has been applied as tool to gain original insight regarding skin temperature patterns across the body in exercise and during cold (Fournet et al. 2013) and hot (Gerrett et al. 2015) exposure. This information can find application in clothing development using a bodymapping approach, e.g. with spatial variations in textile type. Despite the wide range of applications, it has not been reported whether IRT can be applied to quantify sweat retention in clothing, following physical exercise. When the garment is on the body, its temperature is the result of dry heat loss to the environment, evaporative heat loss from the wet areas and heat input from the skin. However, when taken off the body, garment areas presenting higher sweat content would be affected by higher local (evaporative) cooling, resulting in higher temperature drop (from dry), therefore a relationship between local sweat/water content and local temperature drop was expected. As such, in this study spatial and temporal sweat absorption data (obtained from our previous study) were correlated with spatial and temporal temperature data, measured using infrared thermography. Taking into account the influence of body skin temperature on local garment temperature, which could affect the hypothesised relationship between local sweat content and temperature, in the current study infrared image acquisition was performed after removal of the T-Shirt from the body.

Acknowledging the lack of time- and cost-effective test methods, the ultimate goal of this study was to assess whether IRT could be used as an indirect method to estimate garment regional sweat content in a quick and 'non-destructive' fashion. Furthermore, the fast image acquisition could allow assessments of garment sweat content immediately after physical exercising, minimising the risk for moisture migration and moisture evaporation from the garment, which is the main drawback of some lengthy tests (Tang et al. 2014b).

8.2 Method

The infrared images of the garments were collected in parallel with the data collection conducted for our previous study (Study 5). Therefore, participants, exercise protocol and conditions were the same as those in ref. The latter are described below.

8.2.1 Participants

Eight male, long distance runners were recruited from the Loughborough University student cohort. Participants' characteristics (mean and standard deviation) are reported in Table 1.

Table 1 Participants' characteristics.

	Age (years)	Weight (Kg)	Height (cm)	BSA (cm^{-2})	Body fat (%)	VO_{2max} ($mL \cdot Kg^{-1} \cdot min^{-1}$)	Running speed ($km \cdot h^{-1}$)
MEAN	23.3	70.0	177.3	1.9	9.6	62.1	12.1
STDEV	4.7	9.9	5.3	0.1	4.5	3.1	0.7

BSA = body surface area. VO_{2max} = maximum oxygen uptake. STDEV = standard deviation

8.2.2 Experimental conditions

Sweat absorption and temperature across the T-Shirt were mapped over a total running time of 50-min. As a 'destructive' gravimetric method was adopted to quantify regional sweat absorption, each participant performed 10 running trials on a treadmill, characterised by different durations: 5 MIN, 10 MIN, 15 MIN, 20 MIN, 25 MIN, 30 MIN, 35 MIN, 40 MIN, 45 MIN and 50 MIN. Immediately after each partial running trial, the T-Shirt was dissected into 22 different regions of interest (ROI), presented in Figure 1. Using a gravimetric approach (wet weight – dry weight) the time-course and distribution of sweat absorption of each garment was defined (ref). 21 ROI were examined to extrapolate regional temperature data from each thermogram (the collar was excluded for practical reasons). After removal from the body, two infrared images of the T-Shirt, one for the front and one for the back, were taken for each participant, at the end of each running trial. Therefore, for each person, with 10 trials and 2 pictures per trial, 20 thermograms were taken; 160 in total. A procedure similar to that developed by Fournet (2013) was adopted to obtained quantitative temperature data of the ROI and to provide average thermal patterns (temperature distribution across the garment), visually accessible with a colour scale. The experiment was conducted in a climate-controlled chamber maintained at 27.2 ± 0.2 ºC, 49.7 ± 3.2% relative humidity and 1.5 $m \cdot s^{-1}$ wind speed.

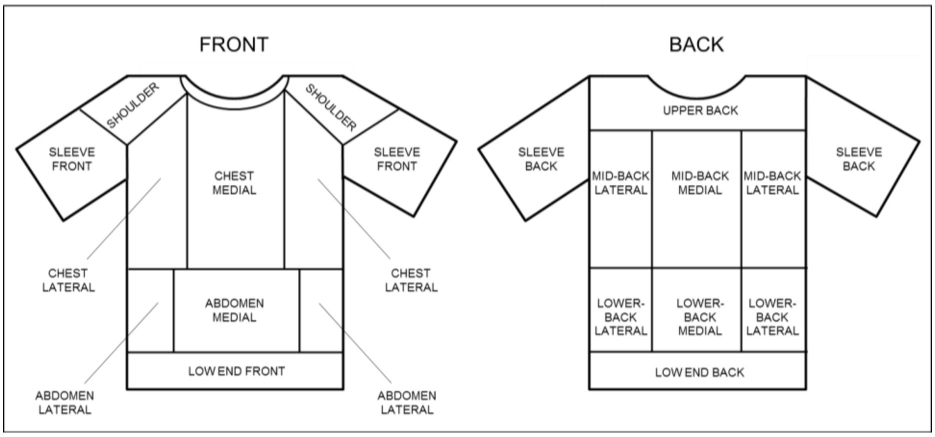

Figure 1 Schematic representation of the experimental T-Shirt marked into the 21 regions of interest for the analyses of local sweat accumulation. Front and back of the T-Shirt were mapped into 11 and 10 zones, respectively.

8.2.3 Experimental garment

A short sleeved, 100% cotton T-Shirt was used for each of the 10 run durations. The T-Shirt presented a regular fit and a surface area of approximately 0.8 m^2. Specifications of the experimental garment are reported in Table 2.

Table 2 Specifications of the experimental garments

Fibre content	Mass ($g \cdot m^{-2}$)	Thickness (mm)	R_{cf} ($m^2 \cdot {}^{o}C/W$)	R_{ef} ($m^2 \cdot Pa/W$)	Air perm ($mm \cdot s^{-1}$)	Absorption ($g \cdot m^{-2}$)
100 % cotton	159	0.55	0.02	3.1	780	381

R_{ct} = dry thermal resistance; R_{ef} = water vapour resistance, Air perm = air permeability, Absorption = total absorption capacity. Dry thermal resistance and water vapour resistance were measured according to BS EN ISO 11092:2014, air permeability was measured according to BS EN ISO 9237:1995; total absorption capacity was measured according to the absorption capacity test adopted by Raccuglia et al.(2016), modified from Tang et al. (2014).

8.2.4 Infrared thermal camera

A FLIR T620 (FLIR Systems Inc. Wilsonville, USA) infrared camera was used. The camera has an operating temperature range between -15 and +50 ^{o}C, and an object temperature range between -40 and +150 ^{o}C, which encompasses the temperature range we aimed to examine (20 – 30 ^{o}C). The camera has a 640 x 480 pixel infrared resolution and the spectral range is 7.5 – 14 µm. The accuracy of the camera is of ± 2^{o}C, which is low compared to the accuracy of other commonly used contact methods (± 0.5 – ± 0.1) (Fournet 2013). For this reason, a black body calibrator was included in the procedure to overcome this limitation. Despite the poor accuracy, the camera presents a very high thermal sensitivity of ± 0.04 ^{o}C. The high thermal sensitivity allowed detection of very small spatial and temporal changes in the temperature of the garment, which is crucial in a temperature mapping approach.

As apparent temperature differences in thermograms can arise from potential curvatures when the obliquity is larger than 45^{o} (Watmough et al. 1970), it is important to point out that, the quality of the measurement was not affected by geometry-related issues, due to the flat shape of the garment.

8.2.5 Image acquisition

A standardised procedure was developed for the acquisition of the infrared images. At the end of each running trial, the wet garment was removed from the body and fitted to a custom-made T-Shirt-like shape wooden stand (Fig 2), which was treated with a hydrophobic finish to prevent water transfer from the T-shirt to the stand. Image acquisition occurred always 3 minutes after taking the T-Shirt off the body to allow the textile to cool. The stand was positioned at a fixed location and the camera was fitted to a tripod, at a distance of 2 meters perpendicular to the T-Shirt stand. The black body calibrator was included in the background of each thermogram (Fig 2) so that potential measurement errors could be reduced.

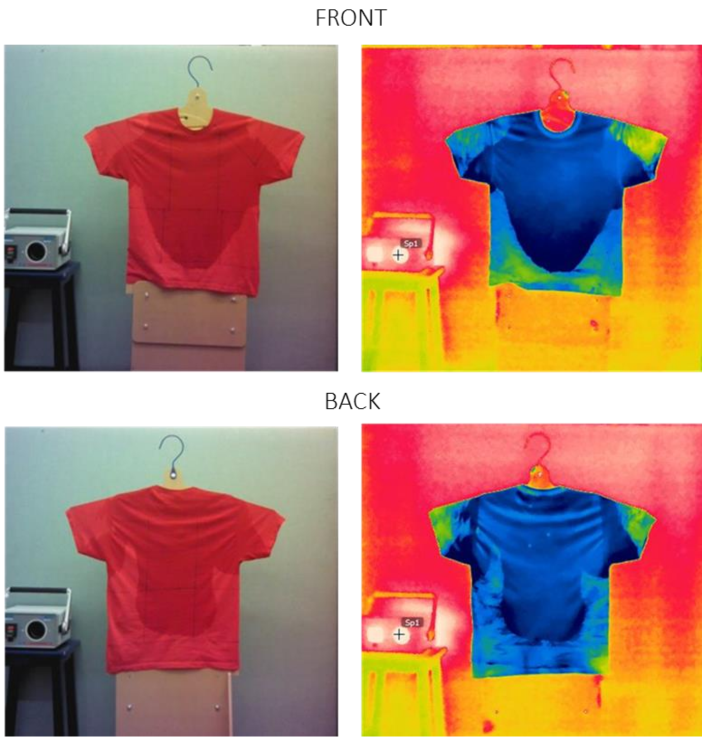

Figure 2 Digital and Infrared pictures of identical views for front and back of the T-Shirt, including black body calibrator positioned on a stool behind the T-Shirt stand.

8.2.5 Image processing

Image processing was performed with three main goals (Fournet 2013). The procedure allowed: (1) standardising the analysis of the numerous thermograms; (2) segmentation of each thermogram in the 21 ROI as well as extrapolating the important spatial temperature data of each ROI; (3) creating average thermograms of the T-Shirt at each time point (trials, from 5 to 50 min run duration).

The development of the image processing procedure was performed using the software MATLAB 7.8.0 (MATLAB R2013a, The MathWorks Inc., Natick, USA). Matlab scripts modified from those developed by Fournet (2013) were used for the analysis. The image processing involved: morphing, averaging and creation of average maps for each trial (time point). Specifically, to account for differences in T-Shirt size and position (although it was standardised as much as possible with the T-Shirt stand), all thermograms were morphed (i.e. adapted) onto a reference T-Shirt shape. Following from this, the individual morphed thermograms were averaged to obtain a final single T-Shirt map of temperature distribution, for each running duration. Figure 3 summarises the different stages of the image processing procedure. Furthermore, after being morphed each thermogram was segmented into the 21 ROI, according to Fig 1 and regional temperature data ($Temp_{Local}$) were computed to calculated average, median, minimal and maximal temperature, standard deviation.

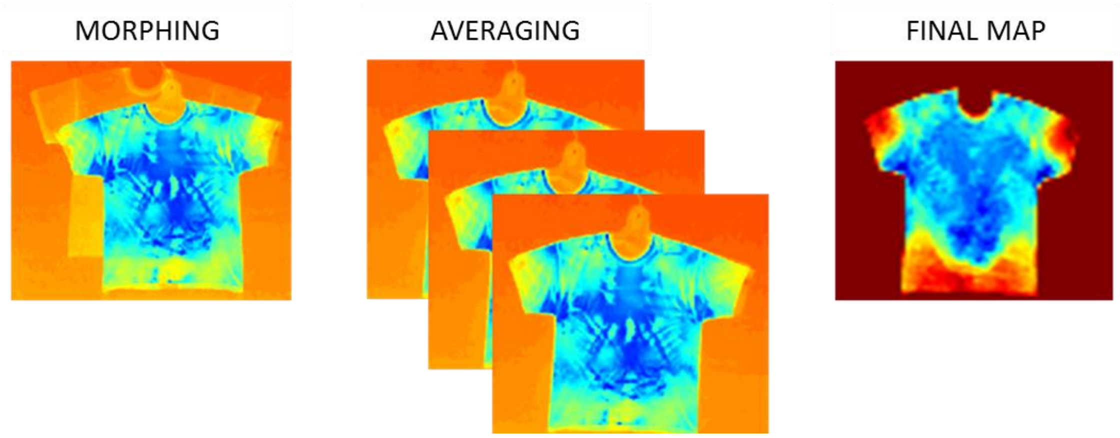

Figure 3 Image processing sequence using MATLAB. Each individual thermogram is morphed to the reference thermogram. The individual thermograms are then averaged for for the creation of a final T-Shirt map of temperature distribution.

Due to the evaporative cooling provided by the presence of liquid sweat, we hypothesised that garment regions with greater sweat content will result in lower temperature as compared to the temperature of the T-Shirt in dry state. As in dry state the temperature of the T-Shirt by definition equals ambient temperature, the temperature of each garment region was considered as temperature drop from ambient temperature (Temp-$Drop_{Local}$), according to:

$TempDrop_{Local}$ (^{o}C) = $T_{ambient}$ -$Temp_{Local}$

Where

$Temp_{Local}$ = garment local absolute temperature in ^{o}C

$T_{ambient}$ = temperature of the ambient air in ^{o}C

8.3 Statistics

Regression analyses were performed to study the relation between garment local sweat absorption (ABS_{Local}) and temperature data ($Temp\text{-}Drop_{Local}$). The regression analyses were performed using different data sub-sets. One regression model included participants' individual data for each ROI at all running durations (8 participants * 21 ROIs * 10 running durations). Another model included participants' average data of the ROIs at all running durations (21 averaged ROIs * 10 running durations). Temporal models, including participants' average data of the ROIs, were provided separately for four selected individual running durations (15 min, 25 min, 35 min and 50 min) (21 averaged ROIs * 1 running duration).

ABS_{Local} was plotted versus $Temp\text{-}Drop_{Local}$ at each running duration (5-50 min) for single selected ROI (chest medial, back upper, shoulder, back mid lateral, shoulder, abdomen medial, low end back) (10 running durations * 1 averaged ROI) and descriptive statistics were performed.

The assumption of normality of distribution of the residuals was checked with histograms and Normal P-P plots. The assumption of homoscedasticity of the residuals was checked using scatter plots of the studentised residuals against unstandardized predicted values. When these assumptions were violated data transformations were conducted.

To characterise the strength of the relations, coefficient of determination (r^2) as well as standard errors of the estimate (SEE) were calculated. Data were analysed using the software IBM SPSS Statistics (version 22) (IBM, USA).

8.4 Results

Temperature and sweat maps of front and back side of the garments are illustrated in Figure 4A and 4B.

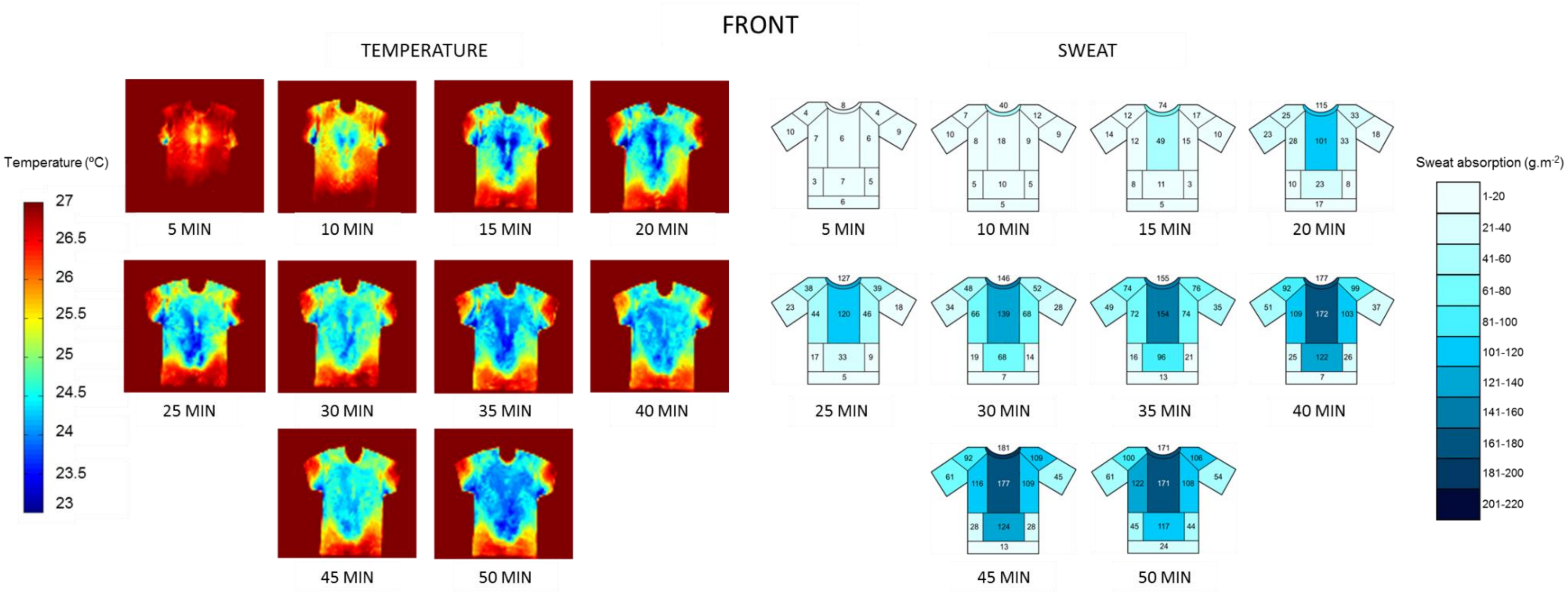

Figure 4A Average (8 participants) maps of temperature (*left*) and sweat (*right*) distribution across the front side of the garments, over 50 min of running exercise. Data for each time point were obtained from 10 different running trials.

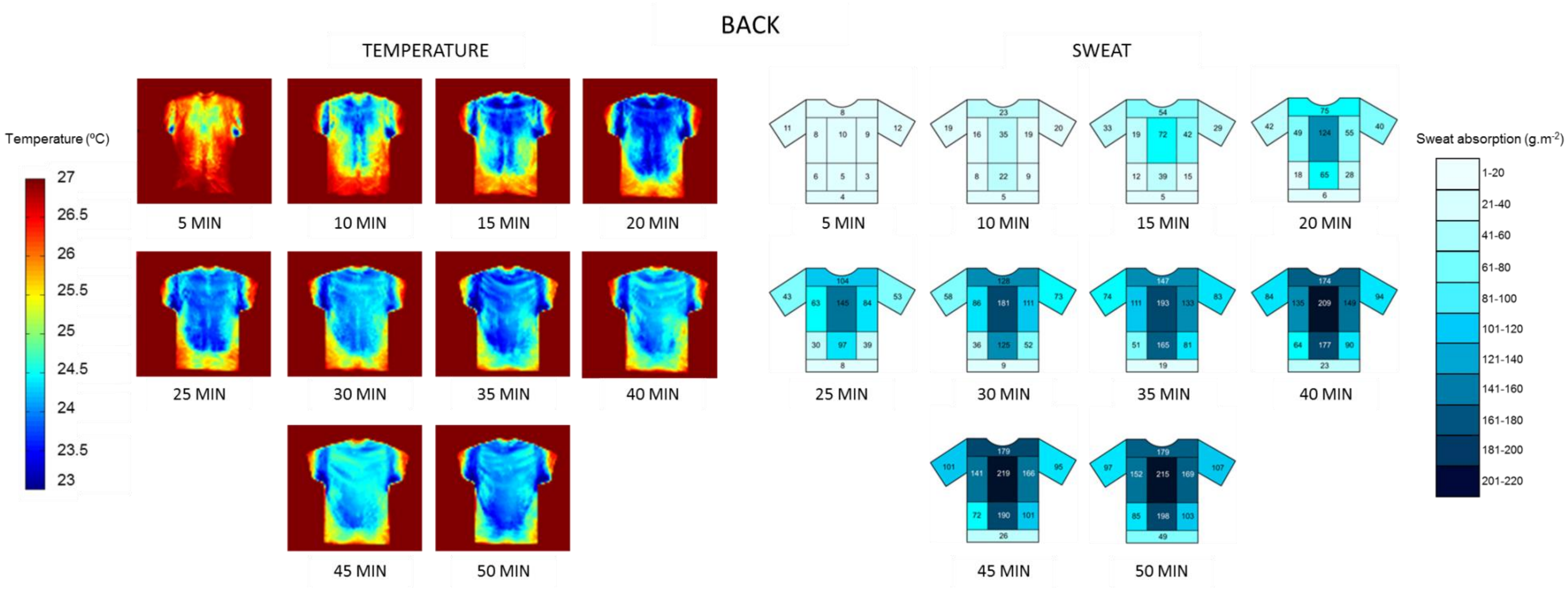

Figure 4B Average (8 participants) maps of temperature (*left*) and sweat (*right*) distribution across the back side of the garments, over 50 min of running exercise. Data for each time point were obtained from 10 different running trials.

8.4.1 Regression models

ABS_{Local} ranged from 0 to 293 g·m^{-2} and $TempDrop_{Local}$ ranged from 0 (no drop) to 4.3 ^{o}C.

Whilst an exponential function was found to best describe the data (Fig 5A), the assumptions of normality of distribution and homoscedasticity of the residuals were violated, hence data transformation was required.

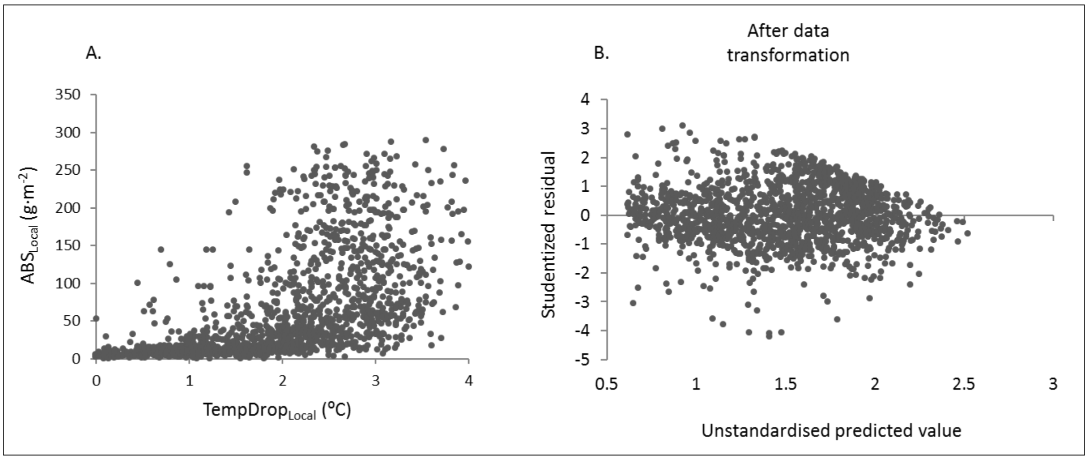

Figure 5A Exponential relationship between local sweat absorption (ABS_{Local}) and local temperature drop ($TempDrop_{Local}$). The model includes participants' individual data for each ROI at each running duration (8 participants * 21 ROIs * 10 running durations). **5B** Plots of Studentized residuals against unstandardized predicted values, after data transformation.

Data transformation included an exponential transformation of Temp-Drop$_{Local}$ ($e^{TempDropLocal}$) and a logarithmic transformation of $e^{TempDropLocal}$ ($^{10}Log\ (e^{TempDropLocal})$) and ABS_{Local} ($^{10}LogABS_{Local}$). After performing data transformation, the residuals displayed a normal distribution and homoscedasticity (Fig 5B). The predictive power of the regression model was statistically significant ($p < 0.001$) but the coefficient of determination was relatively low ($R^2 = 0.52$) (Table 3, overall individual model).

The assumptions of normality of distribution and homoscedasticity of the residuals were also violated in the overall average model (21 ROIs averaged over participants * 10 running durations). As such, the same transformations were applied to the two variables, considered as $^{10}Log(e^{TempDropLocal})$ and $^{10}LogABS_{Local}$. The overall average model presented higher coefficient of determination ($R^2 = 0.75$), compared to the individual model and also reached statistical significance ($p < 0.001$) (Table 3, overall average). The predictive equations of the individual and average overall models are reported in Table 4.

Table 3 Summary of the overall (individual and average) and temporal model and variables included.

Model		Predicted variable	Independent variable	R^2	SEE	Sig.
Overall Individual		$^{10}Log(ABS_{Local})$	$^{10}Log(e^{TempDropLocal})$	0.52	0.40	< 0.001
Overall average		$^{10}Log(ABS_{Local})$	$^{10}Log(e^{TempDropLocal})$	0.75	0.25	< 0.001
Temporal	15 min	ABS_{Local}	$e^{TempDropLocal}$	0.75	8.12	< 0.001
	25 min	ABS_{Local}	$e^{TempDropLocal}$	0.87	11.67	< 0.001
	35 min	ABS_{Local}	$e^{TempDropLocal}$	0.82	28.63	< 0.001
	50 min	ABS_{Local}	$e^{TempDropLocal}$	0.88	21.81	< 0.001

SEE = standard error of estimate.

Table 4 Predictive equations of overall individual and average model as well as temporal models describing the statistical relation local sweat absorption (local temperature drop.

Model		Equation
Overall Individual		$^{10}Log(ABS_{Local}) = 0.615 + 1.014\ ^{10}Log(e^{TempDropLocal})$
Overall average		$^{10}Log(ABS_{Local}) = 0.517 + 1.244\ ^{10}Log(e^{TempDropLocal})$
Temporal	15 min	$ABS_{Local} = 3.322\ e^{0.9397\ TempDropLocal}$
	25 min	$ABS_{Local} =3.9942\ e^{1.1368\ TempDropLocal}$
	35 min	$ABS_{Local} = 3.6698\ e^{1.2211\ TempDropLocal}$
	50 min	$ABS_{Local} = 12.919\ e^{0.8566\ TempDropLocal}$

Exponential curves were found to best fit the relation between ABS_{Local} and $TempDrop_{Local}$, at each selected running duration, i.e. 15 min, 25 min, 35 min and 50 min (Fig 6), with curves shifting up and left with advancing time. The temporal models were statistically significant ($p < 0.001$) and their predictive power ($R^2 \geq 0.75$)

was higher than the overall models (Table 3). The predictive equations of the temporal models are reported in Table 4.

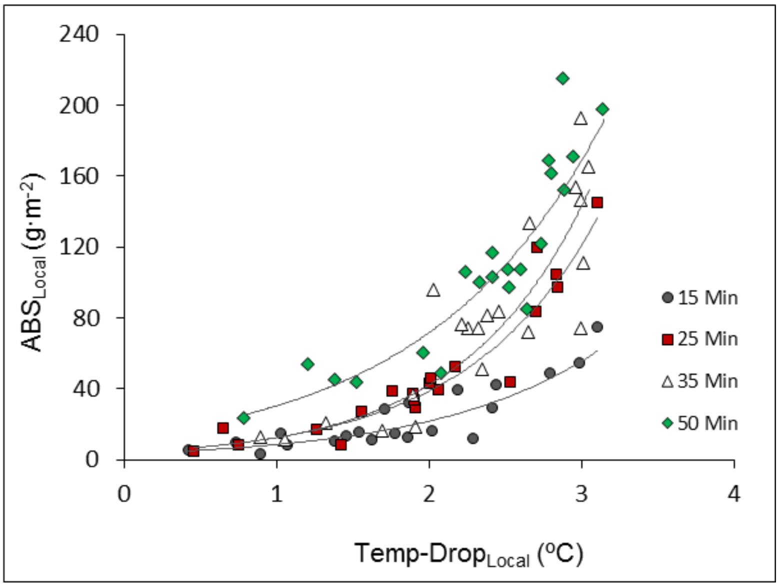

Figure 6 Exponential relationships between local sweat absorption (ABS_{Local}) and local temperature drop ($TempDrop_{Local}$) at selected time points (15 Min, 25 Min, 35 Min and 50 Min). Each model includes participants' average data for each ROI at a single time point (21 averaged ROIs * 1 time point). The coefficient of determination (R^2) of each model is reported in Table 3.

8.4.2 Sweat absorption and temperature in single ROI

In each selected ROI (10 running duration * 1 averaged ROI), the highest value of Temp-$Drop_{Local}$ occurred before ABS_{Local} could reach its highest value (point highilighted in red in Fig 7). Specifically, the highest $TempDrop_{Local}$ was 2.79 ± 0.53 °C for chest medial, 3.24 ± 0.35 °C for back upper, 2.78 ± 0.70 °C for back mid lateral, 2.47 ± 0.67 for shoulders, 1.89 ± 0.69 for abdomen medial, 2.08 ± 0.85 °C for low end back. Highest Temp-$Drop_{Local}$ corresponded to the following ABS_{Local} values, 49.1 ± 40.1 $g \cdot m^{-2}$ for chest medial, 74.8 ± 27.2 $g \cdot m^{-2}$ for back upper, 55.13 ± 30.23 $g \cdot m^{-2}$ for back mid lateral, 47.9 ± 29.2 $g \cdot m^{-2}$ shoulder, 33.3 ± 21.5 $g \cdot m^{-2}$ for abdomen medial, 49.2 ± 31.1 $g \cdot m^{-2}$ for low end back.

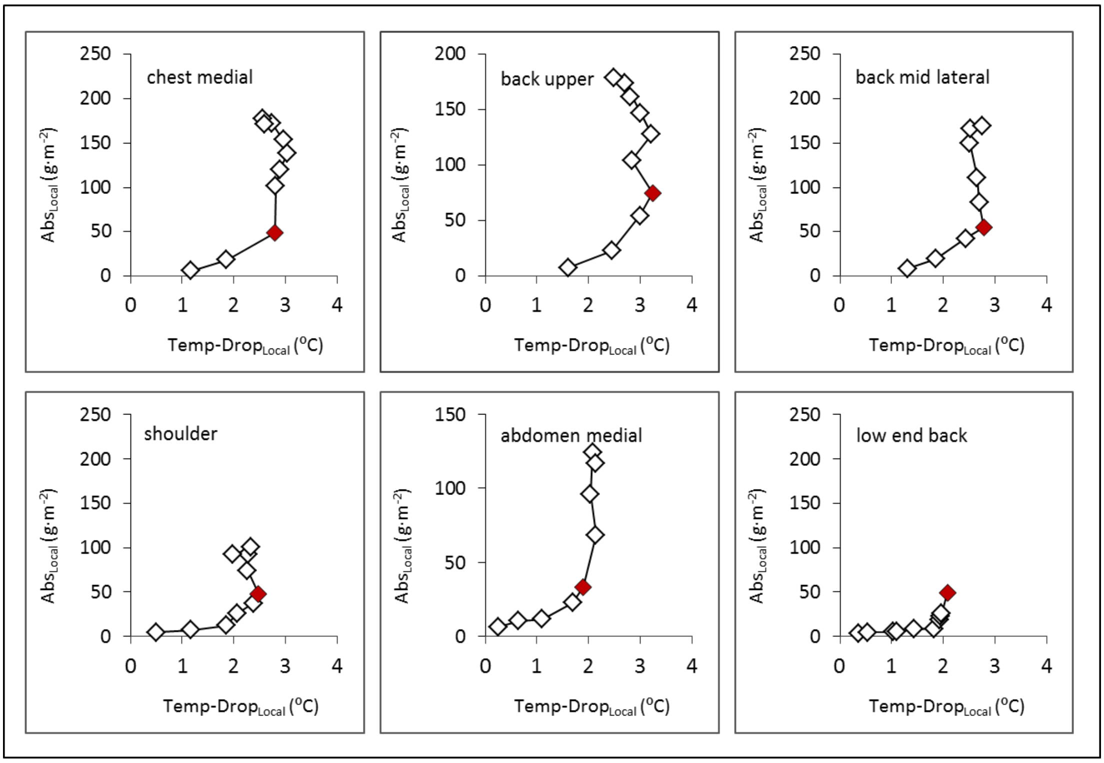

Figure 7 Local sweat absorption (ABS_{Local}) plotted versus local temperature drop ($TempDrop_{Local}$) at each during duration (5-50 min) for selected regions of interest (ROI), i.e. chest medial, back upper, back mid latera, shoulder, abdomen medial, low end back. The red point indicates the highest $TempDrop_{Local}$ and related ABS_{Local} value.

8.5 Discussion

The main focus of this investigation was to determine whether infrared thermography can be used to quantify moisture in garments, by developing a relation between the amount of moisture absorbed and the temperature drop of wet textile areas. Whilst IRT has been adopted to provide maps of temperature distribution across the human body (Fournet et al. 2013), so far IRT has not been used as tool to predict spatial and temporal sweat retention in clothing, after physical exercise. The data suggest that IRT is a good tool to qualitatively predict regional sweat absorption in garments at separate individual time points; however temporal changes are not predicted well, likely due to a moisture threshold causing a temperature limit above which variations in sweat content cannot be discriminated by further temperature changes.

8.5.1 Overall models

We assumed that garment zones characterised by higher sweat retention would be affected by higher evaporative cooling, resulting in higher local temperature drops from their dry state. This was the rationale for attempting to use temperature data to estimate sweat content in clothing. In order to ensure a direct link between garment regional sweat retention and temperature, infrared pictures of the garment were performed after taking the garment off the body. In fact, pilot testing for this study showed that acquisition of the picture while the garment was still on the body gives a combined value of garment and body skin temperature. As such, when the purpose is to assess garment regional sweat content using infrared temperature data, it is important to remove the garment from the body and fit it to a garment-like shape stand. The stand also allows separation of the front from the back T-Shirt's panel (preventing sweat transfer between front and back regions) as well as avoiding infrared transmission from the other side through the garment and ensures a standardised T-Shirt position.

While the overall model including spatial and temporal data of the eight participants was highly significant (individual model, Table 3); regional temperature drop only statistically explained 52% of the variance in regional sweat content (Table 3). This suggests that other factors might have affected the link between these two parameters. The exponential shape of the curves describing the relation between local sweat absorption and temperature indicates that local temperature changes can predict local sweat retention up to a certain moisture saturation value, this being around 50 $g \cdot m^{-2}$ (in a cotton material and in the climatic condition adopted). In line with this, Fig 7 illustrates that in the selected ROIs, the highest temperature drop (~3ºC) is achieved between 50 and 60 $g \cdot m^{-2}$and no further drop occurs beyond these values. This indicates that there is a moisture threshold causing a temperature limit, this possibly due to the attainment of maximum evaporative cooling. The data suggest that above this moisture threshold, variations in locals sweat content cannot be discriminated by temperature changes measured with IRT. In the currently adopted climatic conditions this threshold corresponded to moisture content of approximately 50 $g{\cdot}m^{-2}$, this causing a temperature drop limited to approximately 3 ^{o}C.

Another factor to consider when studying the link between regional sweat retention and temperature drop in clothing is the uniformity of sweat/temperature distribution in each pre-selected garment region. Specifically, the temperature maps in figure 4a (*front*) and 4b (*back*) show that changes in garment regional temperature do not occur uniformly within peripheral and inferior regions (e.g. front and back sleeves, mid back later, chest and abdomen lateral and lower ends). On the other hand, as the gravimetric method only allows an overall measurement of sweat retention in pre-defined regions, the sweat maps suggest a uniform distribution of the sweat absorbed in each region (Fig 4a and 4b). This discrepancy could have affected the link between sweat retention and temperature change in those regions presenting a non-uniform sweat distribution. Finally, the climatic condition adopted is another variable that can influence the relation between regional sweat retention and temperature drop. For instance, for the same garment saturation level, a higher temperature drop is expected in a dryer environment, as compared to the current conditions adopted (50% rh). As such, while the studied principle remains the same, different regression equations would need to be used if different climatic conditions are applied.

When participants' average data of each ROI are used, rather than all individual data points, a better prediction model, as compared to the individual one, is obtained (r^2 = 0.75, Table 3). As such, in some research settings, i.e. in studies involving within-subjects comparisons of different T-shirts, shorts or trousers etcetera, the use of participants' average data could improve the predictive power of regional sweat content.

8.5.2 Temporal models

While in the overall individual model regional temperature can only explain 52% of the variance in garment local sweat retention, temporal average models, including sweat and temperature data for separated exercise durations (Fig 6), present a stronger predictive power (r^2 = 0.75-88). Nevertheless, Figure 6 shows that with the increase in exercise duration (highlighted in each separated model) and local sweat retention, the curve moves up and the slope becomes progressively steeper rather than developing towards the right side of the graph (increase in temperature drop). As indicated earlier, above a certain value, the increases in sweat retention, which occur as exercise time and sweat production progress, are not accompanied by concomitant increases in temperature drop. This again clearly shows that there is a temperature limit above which increases in sweat retention cannot be discriminated by using temperature drop values. Since sweat retention mainly changes as function of time, the overall model, including the temporal changes, is highly affected by this ‘threshold effect’ and shows a lower predictive power as compared to the single temporal models. However, such different temporal models at different exercise times would not be stable and would change with any change in condition. Thus, these are not practical in their application for quantitative sweat absorption determinations. As these temporal models do not allow accurate predictions of sweat retention between different exercise duration/intensity, IRT cannot be used to reliably quantitatively assess the development of sweat retention over time and across garment regions, unless sweat absorption remains very low. Nevertheless, the strong coefficient of determination of the temporal models indicates that IRT can very well be used to make qualitative inter-regional assessment of sweat retention, i.e. to define regions with high or low sweat content.

8.6 Limitations

The impact of body skin temperature on garment regional temperature was minimised by removing the garment from the body and allowing some time before performing the image acquisition. This time needs to be long enough in order to remove the effect of skin variations and allow a steady-state garment temperature to be developed, but short enough to avoid sweat migration. In a pre-test we observed that, in the first 3 minutes immediately after T-Shirt removal, garment temperature dropped from 26 ^{o}C to 21.7 ^{o}C, leading to a difference of approximately 4 ^{o}C. Natural wet bulb temperature (as indicator of the maximal temperature drop possible) in the climatic condition used was 20.8 ^{o}C, therefore approximately 6 ^{o}C difference from ambient temperature (27 ^{o}C). However, although natural wet bulb temperature indicates that the limit for evaporative cooling was not achieved within the 3 minutes, the data showed that the highest relative change of garment temperature (1 ^{o}C) occurs during the first minute, immediately after fitting the garment on the stand. After 2 minutes, this relative change accounts for 0.4 ^{o}C and after 2.5 min to 8 min the relative change in garment temperature is very small (0.1 ^{o}C). Based on these data, a stabilisation period of 3 minutes was chosen, given that a longer stabilisation period between garment removal from the body and image acquisition could cause sweat migration across proximate regions.

Furthermore, a non-uniform contact between the T-shirt stand and garment could have affected the garment's temperature. Therefore, for future studies a stand which has minimal contact area with the T-Shirt, for instance a wire frame only in contact with the inner contour of the T-Shirt, yet allowing separation of the front and back garment's side, is proposed.

8.7 Conclusions

In this research infrared thermography was used as a tool to indirectly quantify spatial and temporal variations in clothing sweat absorption, immediately after physical exercise of different duration/intensity. In order to minimise the impact of body skin temperature on garment local temperature, infrared image acquisition has to be performed after removal of the garment from the body, and after fitting it to a garment-shape stand. It can be concluded that, based on differences in local temperature drop (from dry state), IRT allows discrimination of higher and lower regional sweat retention, in a 'non-destructive' way. Furthermore, IRT can be applied to make more precise qualitative assessments with regards to the level of sweat (temperature) distribution within a certain region, whereas the gravimetric method assumes uniformity of sweat retention in a pre-defined garment region. Nevertheless, despite these benefits, this study highlighted a number of limiting factors that preclude the use of IRT for quantitative estimations of spatial and temporal sweat retention in garments, when evaluations need to be performed within a relatively short time after exercise, with the main limitation being a moisture content threshold above which no further effect on temperature is observed.

CHAPTER 9

Conclusions

Discussion applications limitations and future directions

9.1 Introduction

The main focus of this doctoral research was to identify the main textile and clothing parameters modulating the cutaneous sensations and perceptions occurring under conditions of skin and clothing wetness. Since the current literature review established that material test methods cannot comprehensively describe clothing functionality and their impact on human responses, a research methodology including both material and human assessments was developed. According to this research methodology, the main textile properties affecting wetness-related and discomfort sensations in humans were identified. Finally, in order to guide the process of clothing development, using a sweat mapping approach, temporal and spatial changes in sweat retention were mapped in an upper body garment worn by male athletes in exercise.

9.2 Textile parameters modulating cutaneous sensations and perceptions occurring in conditions of skin and clothing wetness

In this research, the textile parameters indicated as major determinants of fabric absorption capacity and related perceptions were thickness/volume, 'wet' weight, moisture saturation percentage, surface area and surface texture.

9.2.1 Thickness

In Study 1 (Chapter 3) fabric thickness was shown as a major parameter determining moisture retention in textile materials and skin wetness perception. Specifically, in static fabric-to skin contact conditions and in fabrics in steady-state of absorption (pre-wetted fabrics), higher thickness resulted in higher water retention values. These absorption values were obtained using a gravimetric water absorption capacity test, where the fabric is fully immersed in water (Tang et al. 2014a). When wetted with the same moisture saturation percentage (100% and 50% of the maximum absorption capacity), fabrics presenting greater thickness, caused higher wetness perception responses. As such, fabric thickness was indicated as main predictor of wetness perception (Raccuglia et al. 2016a). The investigated fabrics presented same surface area (cm^2), similar density and capillary volume. However, differences in these above-mentioned parameters could impact fabric absorption capacity (Jeon et al. 2011) but also the relation between wetness perception and fabric thickness found in Study 1 (Raccuglia et al. 2016a). In steady-state of absorption, fabrics with different fibre compositions, but same thickness, did not result in different wetness perception responses (Raccuglia et al. 2016a). However, future studies should look at the impact that fibre composition and related-hydrophilicity could have on absorption rate and related moisture sensation in transient absorption conditions.

9.2.2 Fabric 'wet' weight

In Study 1 (Chapter 3) it was observed that the weight of the fabric in wet state can also modulate wetness-related perceptual responses (Raccuglia et al. 2016a). Specifically, by manipulating the level of fabric-to-skin pressure 'heavier' fabrics were perceived wetter than 'lighter' ones, despite using the same fabric and applying the same level of physical moisture. This phenomenon was explained in light of the 'synthetic' nature of wetness perception and the sensory modalities underpinning it, specifically through the effect of fabric weight on cutaneous perceived pressure which was associated with higher physical wetness in fabrics.

9.2.3 Moisture saturation percentage

Due to the link identified between fabric water content and thickness/volume, fabric saturation percentage was indicated as parameter to take into account when interpreting moisture-related responses elicited by wet fabrics (Raccuglia et al. 2016a). When fabrics characterised by different thickness/volume are treated with the same moisture saturation percentage (relative to the maximum absorption capacity), thinner fabrics are perceived less wet than thicker ones, as thicker fabrics present higher absolute water content, causing higher cooling and pressure sensations, associated with higher wetness. On the other hand, when fabrics are treated with the same absolute water content, thinner fabrics present higher amount of water per volume of fabric and therefore higher saturation percentage, therefore these fabrics are perceived wetter than thicker fabrics, the latter being less saturated (smaller amount of water per unit volume of fabric).

9.2.4 Total surface area

In Study 4 (Chapter 6), the significant impact of fabric moisture saturation on wetness-related sensorial responses, i.e. wetness and stickiness sensation, was studied in exercise-induced sweat production conditions. Stickiness sensations are typically elicited by the tactile interaction between the wet fabric and the skin. In Study 4, higher garment moisture saturation percentages resulted in greater sensations of stickiness (Raccuglia et al. 2017a, 2017b). Differences in saturation percentages, caused by sweat absorption, were obtained by manipulating the total area of the fabric in contact with the skin. The lower surface area available for sweat absorption, which was achieved by higher perforation levels of the fabric, also concentrated the absorbed sweat in a smaller area, which led to higher moisture saturation (higher amount of sweat per unit area available). Interestingly, the garment with the higher saturation percentage (in relation to surface area, $g \cdot m^{-2}$) presented the lowest absolute sweat content value (g) and resulted in higher stickiness sensation, although wetness perception being the same between the garments. This confirmed the stronger impact of moisture saturation compared to absolute moisture level in fabrics. Therefore, fabric thickness and fabric total surface area (through its impact on garment moisture saturation) are crucial parameters modulating moisture-related sensation resulting from wet fabrics, in this case stickiness sensation.

Since differences in moisture saturation between garments led to differences in stickiness sensation but wetness perception was the same, this study demonstrated that stickiness and wetness should be considered individually and should not be used as interchangeable terms. In fact, although stickiness sensation is strongly related to wetness perception (Raccuglia et al 2017b), in some conditions, i.e. when cold cues are restricted (sweat induced-sweat production in warm environments) tactile sensations (stickiness) do not impact wetness perception responses (Study 4). As such, in these conditions, stickiness sensation, rather than wetness perception, is a better parameter to consider when studying differences in wear dis(comfort) between garments.

9.2.5 Surface texture

In study 2 (Chapter) pre-wetted fabrics were applied in dynamic contact with the inner forearm skin (skin regional study). It was observed that sensations of stickiness are higher in fabrics with smoother surface texture (Raccuglia et al. 2017b). The wet smoother fabric surfaces can create higher contact with the skin, this resulting in higher skin displacement and friction and sensed as higher stickiness. Stickiness sensation was linearly and positively related with wetness perception. Interestingly, the power of wetness perception prediction became stronger when including both stickiness sensation and fabric thickness as predictors. Even in this case, it should be noted that stickiness sensation drives tactile sensations modulating wetness perceptions, however the two parameters (stickiness and wetness) should be considered individually. In this mechanistic study, fabric moisture content was manipulated by the investigator to obtain same moisture saturation percentage between fabrics (50% of the total absorption capacity). However, as observed in exercise-induced sweat production conditions (Study 4, Chapter 6), changes in moisture saturation, resulting from different fabric surface areas for absorption, can dominate that impact of fabric texture on stickiness sensation.

The latter clearly shows that in a multifactorial system such as the environment-human-clothing one, the strength of different cutaneous moisture-related stimuli, triggered by various textiles parameters, should be considered. Furthermore, this indicates that, to obtain a better understanding of clothing performance and its impact on human sensations, human assessments should be conducted using a holistic approach, i.e. skin regional and whole body studies (mechanistic as well as applied method).

9.2.6 Limitations

In the first phase of this PhD research, fabrics were pre-wetted and applied on the dry skin. When pre-wetting fabrics, the investigator has to decide between adding the same relative water amount or the same absolute water amount to the tested fabrics. As mentioned, these two different wetting procedures can lead to different sensorial and perceptual outcomes, related to fabric thickness and moisture distribution (Raccuglia et al. 2016a). In addition to the wetting procedure, the investigator has to decide between using fabrics in steady-state of absorption (fabrics are pre-wetted and then time is allowed for the water to spread evenly across the fabric) or in dynamic absorption conditions (water is added to the fabric which are then immediately applied to the skin). In the first laboratory study (Chapter 3) the main aim was to identify differences in wetness-related sensations and perceptions between the two wetting procedures, i.e. relative versus absolute water content. In this study, fabrics were examined in conditions of steady-state of absorption, in order to control for other confounding textile variables. In fact, when fabrics are studied in dynamic absorption conditions (not in steady-state) other parameters such as fibre type (i.e. natural versus synthetic), treatments (e.g. hydrophilic, hydrophobic, fabric drying), or structures (e.g. single jersey, double jersey) could impact wetness-related sensorial outcomes. These textile parameters indeed can affect dynamic moisture absorption properties, such as absorption rate, wicking and drying time, which could then determine wetness-related sensorial responses in dynamic moisture absorption conditions. Therefore, future studies should examine the role of dynamic moisture absorption parameters, such as absorption, rate, wicking and drying time on wetness-related perceptions and wear discomfort, in dynamic sweat absorption conditions.

Another methodological approach which could be used to investigate wetness-related responses between different fabrics is to characterise fabric moisture content using a test which is closer to real life dynamic absorption conditions, as compared to the sink test used in this PhD research. More realistic moisture saturation values could also be obtained from studies involving human participants in exercise conditions. These moisture absorption values could then be applied to the tested fabrics to assess the impact on wetness-related sensations and wear discomfort, using a more realistic wetting approach.

9.3 Wetness perception and stickiness sensation in clothing

9.3.1 Pre-wetted fabrics – Mechanistic approach

Despite the absence of cutaneous hygro-receptors (Clark and Edholm 1985), humans can perceive different degrees of skin wetness, through the integration of thermal and tactile cues. In the case of pre-wetted textile materials (water at ambient temperature) contacting the dry skin in static application conditions, participants can perceive various degrees of fabric wetness by integrating fabric thermal (cooling provided) and mechanical (load on the skin) inputs (Raccuglia et al.

2016a). In these conditions, fabric thermal properties under wet state seem to be the main cues contributing to the perception of moisture content. Specifically, with the increase in fabric water content the cooling power, related to the heat capacity of the liquid in the textile, also increases, resulting in higher local skin cooling and wetness perception. The contribution of fabric mechanical input was indicated by the greater wetness perception in heavier fabrics, due to the resultant higher load/pressure on the skin which increases the magnitude of stimulation of both thermo- and mechanoreceptors. With regards to clothing application, this indicated that when designing a garment with reduced wetness perception and discomfort, the factors that should be taken into consideration are the wet weight of the fabric and the resultant local skin temperature drop.

In dynamic contact condition, the mechanical interaction of a wet fabric with the dry skin causes skin displacement. This skin displacement is sensed as stickiness, and represents an important contributing factor to the perception of wetness in fabrics (Raccuglia et al. 2017b). In these conditions stickiness sensations were mainly driven by the surface texture of the fabric, with smoother perceived fabrics being associated with higher stickiness and wetness, despite same moisture saturation percentage.

9.3.2 Fabric wetness induced by sweat production – Applied approach

In exercise-induced sweat production conditions, the substantial and significant differences in sweat content, saturation percentage and also stickiness sensation of garments did not impact wetness perception responses which were almost identical between the garments (Raccuglia et al. 2017a). The latter might not be in line with the results observed in skin regional studies. Nevertheless, it should be noted that in the skin regional studies, fabric moisture content was manipulated by adding water at room temperature to the fabric, this substantially increasing the thermal conductivity of the fabric and acting as a cold cue for wetness perception. On the other hand, it seems that during exercise in warm ambient temperature (Study 4, Chapter 6), sweat evaporation does not provide enough cooling, typically considered one of the thermal cues involved in the perception of skin wetness. Therefore, the current results indicate that when performing physical exercise in warm environments, differences in garment stickiness sensation do not necessarily affect wetness perception. Consequently, in a mild or hot environment, when cold sensory cues are restricted, stickiness sensation seems a more impactful parameter to consider when determining moisture-related differences between garments. Future studies should investigate these avenues under exercise conditions at colder environmental temperature, where the availability of cold cues could have an impact on wetness perception.

9.3.3 Model of wetness-related sensations in the human-clothing system

According to the findings of this PhD research, a model describing the textile factors modulating sensation and perception related to skin and clothing wetness has been provided (Fig 1). In this model, fabric stimulations are detected on the skin, the stimuli (afferent ascending feedback) are then sent to the central nervous system where they are processed and arranged into perceptions. The model includes textile physical properties (*purple*), cutaneous sensory-receptors, such as thermo- (*blue*) and tactile-receptors (*green*) and higher sensory outputs, i.e. thermal sensation (*blue*), stickiness sensation (*green*), wetness perception (*orange*) and wear discomfort (*orange*). This model also includes two scenarios in which physical wetness can be induced (*red*), i.e. laboratory-induced wetness (water at room temperature added to the fabric in contact with the dry skin; Fig 1A) and sweat-induced wetness (both the skin and the fabric are wet; Fig 1B) under heat exposure.

In details, the model (Fig 1A) indicates that fabric thickness, fabric volume and the contact surface area available for sweat absorption have an impact on moisture saturation percentage, absolute moisture content and wet weight of the fabric. The moisture saturation percentage and moisture absolute content stimulate the thermo- as well as tactile receptors, triggering temperature and tactile responses, i.e. cold sensations and stickiness sensations. Fabric weight also stimulates the tactile receptors, sensitive to the load of the wet fabric pressing on the skin and leading to pressure sensations. Fabric surface texture affects the level of contact between the fabric and the skin (contact points), which has an impact on the level of fabric-to-skin friction and skin displacement, determining stickiness sensations. The integration of thermo- (cold sensations) and tactile stimulations (stickiness and pressure sensation) in the central nervous system (CNS) modulate wetness perceptions, which will then cause wear discomfort. Wetness-related sensations and perception can also be modulated by other factors, these related to the modality in which physical wetness is induced, i.e. sweat-induced or laboratory-induced, and to the thermal environment, i.e. hot or cold. In conditions of laboratory-induced wetness (Fig 1A), water is added to the fabric, which is then applied to the dry skin. In this scenario, the high thermal conductivity of the wet fabric triggers cold sensations, which modulate wetness perception independently (static contact conditions), or in combination with tactile sensations, i.e. pressure sensations (static and dynamic contact conditions) and stickiness sensations (dynamic contact conditions only). Under heat exposure and in conditions of sweat-induced wetness (Fig 1B), both the skin and the textile are wet and sweat temperature is at skin temperature. In this scenario, conductive cooling is negligible and sweat evaporation does not always reduce skin temperature due to a high supply of warm blood, thus not affecting cooling sensations. As such, in this condition, stickiness sensation is the main outcome that allows discriminations between wet garments and affects wear discomfort. Nevertheless, the impact of cold sensations in conditions of sweat-induced wetness where cold cues are largely available, i.e. cold exposure, requires future investigations.

These findings indicate that previous models of cutaneous wetness perception postulated by Filingeri et al. (2014a) are unable to explain the sensory mechanisms underpinning wetness-related sensations and perceptions in relation to textile materials and in conditions of sweat-induced wetness. In fact, the current research demonstrated that thermo- and tactile cues are triggered not only by the amount of physical wetness but also by the textile parameters above reported. Wetness-related sensations and perceptions are also affected by the modality in which skin wetness is induced, i.e. pre-wetted fabrics, or sweat-induced skin and garment wetness. Previous models (Filingeri et al. 2014a) indicate that wetness perceptions occur from the central integration of tactile and cold stimulations at skin level. When cold stimulations are restricted, tactile (stickiness) sensations represent the main cues modulating the perception of wetness (Filingeri et al. 2015). On the contrary, the current PhD research demonstrated that changes in stickiness sensations do not necessarily affect changes in wetness perceptions. In fact, although in some conditions (i.e. in combination with cold cues) stickiness sensation is highly related to wetness perception, when cold cues are restricted, stickiness sensation is not directly associated to wetness perception and can independently influence wear discomfort. As wetness-related sensations can reduce human productivity and performance as well as users satisfaction, through their impact on wear discomfort, in the current model (Fig 1) wear discomfort was integrated and considered as main outcome.

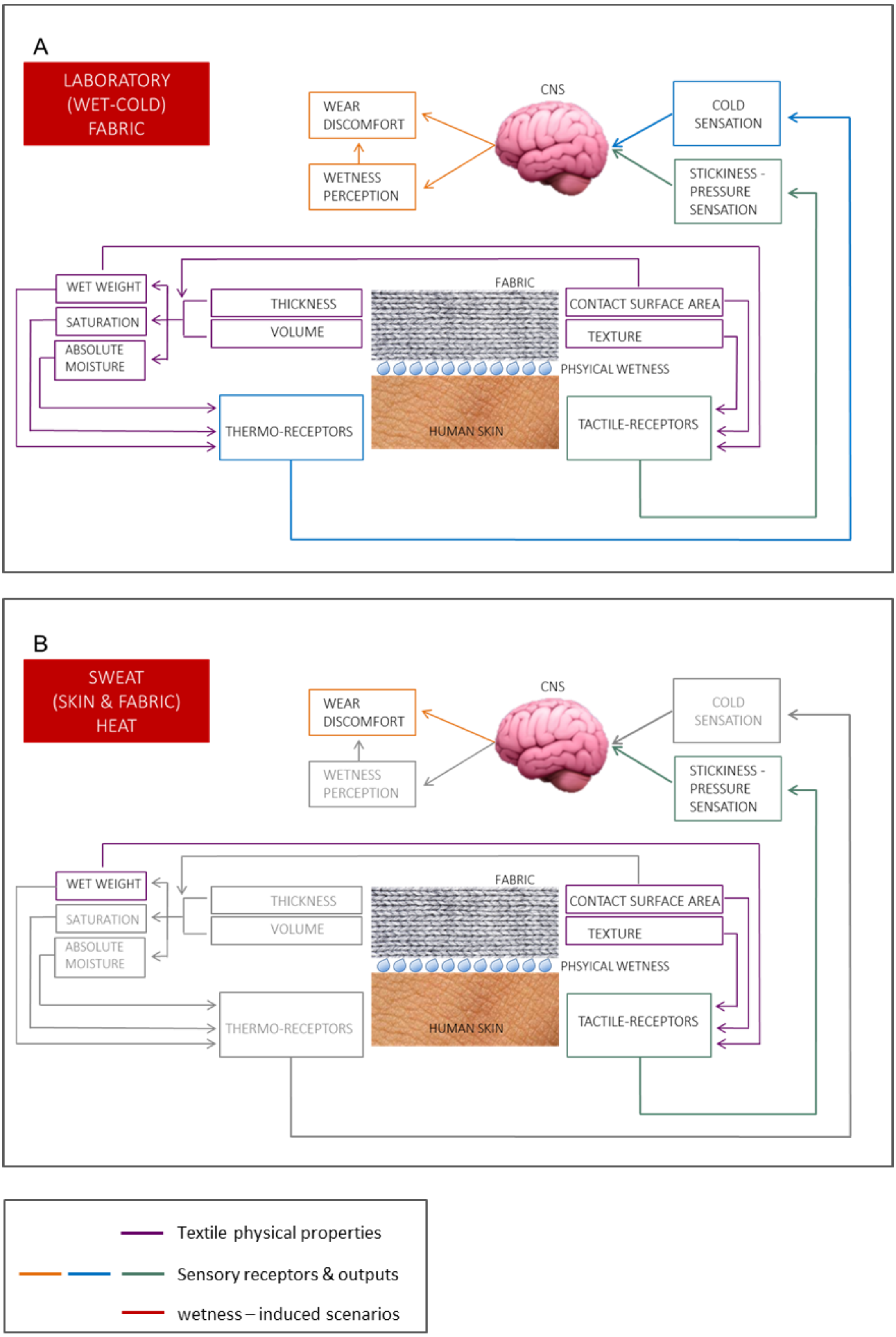

Figure 1 Model of wetness-related sensations in the human-clothing system, in (A) laboratory-induced and (B) sweat-induced wetness conditions.

9.4 Human wear discomfort

Comfort is a criterion commonly used by the users when selecting clothing. Sensations of discomfort can also impact human productivity and mental as well as physical performance (Parsons 2014; DenHartog and Koerhuis 2017).

The presence of wetness at the skin clothing interface is recognised as one of the main sources of discomfort in wear conditions. It was shown that the perception of wetness in fabrics is strongly and positively related to thermal discomfort (Raccuglia et al. 2016a). This was mainly due to the increase in the magnitude of cold sensation as fabric water content is increased. The impact of clothing wetness on thermal discomfort should be carefully taken into account when considering cold environmental conditions, or condition in which body temperature suddenly drops, i.e. after physical exercise. In these situations, in fact, body contact with a wet material can increase the rate of body temperature reduction (after chill drop), causing cold sensations and resulting in thermal discomfort.

Together with comfort, pleasantness is a criterion used when selecting clothing. In this research, pleasantness was significantly reduced when fabric texture sensation increased, i.e. in rougher fabrics (Raccuglia et al. 2017b). The significant relation between texture sensation and pleasantness indicates that fabric texture is an important parameter to consider in terms of clothing acceptability, in addition to wetness perception and thermal comfort. Interestingly, in a wet state fabric texture sensation significantly increased (fabrics perceived less smooth) compared to dry state and resulted in a concomitant reduction in fabric pleasantness sensation (Raccuglia et al. 2017b). Therefore, judgements of fabric texture and associated pleasantness can change in relation to the hydration state of the skin and/or fabric moisture content. As such, evaluations of fabric/clothing texture and related acceptability should be conducted under both dry and wet conditions.

The factor/s influencing wear discomfort were defined in exercise-induced sweat production conditions (Study 4, Chapter 6). Whilst no overall model for discomfort could be developed (suggesting complex interactions between the relevant parameters and the time-course development of the relationships), models for different time points were produced. At baseline, when the individuals just wear the garment, wear discomfort is in part affected by sensations of fabric texture (with smooth fabrics perceived as less uncomfortable). The influence of texture sensation on wear discomfort, during the initial interactions of the garment with the skin, explains why garment texture may be a parameter partially affecting the buying decision process of a specific clothing product. On the other hand, with the start of the physical exercise as well as sweating responses, stickiness was identified as the main parameter affecting wear discomfort. These findings indicate that factors influencing the perception of wear discomfort can change over time and in relation to the over-time changes in human thermophysiological responses, such as metabolic rate and sweating.

Although the factors that can contribute to wear discomfort at rest and during exercise were identified, a substantial amount of variance (~ 50%) in discomfort is still unexplained. For this reason, future investigations should address the role that other parameters could play on wear discomfort, to achieve more accurate estimations of wear comfort and to improve clothing performance.

9.5 Maps of sweat distribution in an upper body garment

In Study 5 (Chapter 7) spatial and temporal variations in garment sweat content were mapped in a cotton and synthetic upper body garment. Sweat absorption in both garments increased significantly with exercise duration; however, the rise became less pronounced after approximately 35 minutes of running. After 50 minutes of running exercise, the cotton and synthetic garments reached, on average, only 41% and 18% of the total absorption capacity, respectively. A clear pattern of sweat absorption reduction from the top to the bottom and from the centre to the sides of both garments was observed. The inter-regional differences in garment sweat absorption were explained by the interactions of physiological, anatomical and clothing factors. The highest local moisture saturation was achieved in the mid-medial back and it was around 56% and 35% in the cotton and synthetic garment, respectively. These saturation values were obtained by relating whole and local sweat contents to the absorption capacity of the fabric. The latter was determined using a gravimetric test in which the fabric is completely immersed in water (Tang et al. 2014a; Raccuglia et al. 2016a; Raccuglia et al. 2017b). However, if a test set-up that can better simulate real wear conditions is used, lower absorption capacity is obtained, this resulting in higher total and regional moisture saturation value.

As expected, sweat absorption data were substantially lower in the synthetic garment as compared to the cotton garment; nevertheless, the patterns of sweat distribution appeared to be very similar. These findings nicely demonstrate that differences in textile properties can determine the absolute amount of sweat absorbed and distributed across the garment. On the other hand, garment fit mainly affects the patterns of sweat absorption distribution in clothing, through its effect on fabric-to-skin contact and air gap thickness.

Future studies should investigate total garment sweat absorption and regional sweat distribution patterns in a multilayer clothing system, including base-layer and coverall (cold environmental conditions) and in a bra-T-Shirt clothing system including female participants.

9.6 Overall thesis conclusions

The current research work has identified the textile factors affecting sensations and perceptions related to skin and clothing wetness. This work has shown that wetness perception is not the only sensorial factor contributing to wear discomfort in conditions of skin and clothing wetness. In fact, it was found that stickiness and haptic sensations can also affect wear discomfort and clothing acceptability, even more than wetness perception, especially when exposed to warm/hot environmental conditions. In this regard, a clear distinction between wetness perception and stickiness sensation was made and it was recommended to consider the two as independent sensations/perceptions.

Conclusions regarding the textile factors modulating sensations and perceptions related to skin and clothing wetness have mainly been drawn from objective data obtained from the gravimetric sink test. This test does not simulate sweating conditions as well as other tests, like the GATS test for instance. The gravimetric sink test, rather than the GATS test, was performed due to the restricted accessibility to the latter test, this representing a limiting factor of the current research work.

Although the GATS is a more realistic test than the gravimetric sink test, it has not been validated by moisture absorption and saturation values of clothing when wore by humans. Additionally, Studies 1, 2 and 4 showed the crucial impact of garment saturation on stickiness sensation, wetness perception and related discomfort. Therefore, it was important to gather information regarding sweat-induced moisture saturation values of garments during physical activity. Finally, due to regional differences in body sweat rate and regional difference in skin-to-clothing air gap thickness, it was important to identify garment moisture saturation values at different garment locations. This was the rationale behind Study 5. Related to this, Study 6 aimed to develop a procedure to enable the evaluations performed in Study 5 to be less expensive and time-consuming for future investigations. Specifically, Study 6 assessed the applicability of Infrared Thermography for estimations of garment regional sweat absorption, using changes in temperature of wet garment areas from their dry state.

Apart from studying the specific contribution and effect of the investigated textile parameters on human sensory responses, the overall conclusion of this thesis is that the factors influencing clothing functionality and perceptions of wear (dis)comfort can change over time and in relation to the over-time based changes in human thermophysiological responses, such as metabolic rate and sweating. These changes will in turn affect both thermal and moisture responses as well as haptic responses (i.e. texture sensations) in humans. This indicates that the factors determining clothing (dis)comfort are dynamic and alter importance during physical activity. Based on these findings, this thesis recommends a process of clothing development involving an objective characterisation of the textile properties, followed by skin regional studies, which allow the study of the impact of each single textile property on human sensorial responses. Skin regional studies are then followed by human wear tests, which take into consideration the combined effect of different textile properties as well as their change over time. This human-centred clothing development process will lead to a better understanding of the textile and clothing factors determining wear discomfort. The current approach can be adopted to study other aspects of wear discomfort such as textile factors affecting haptic sensations.

Future studies should account for additional critical factors contributing to wear (dis)comfort during exercise and include other environmental conditions (i.e. outdoor cold conditions), in order to advance predictions of wear (dis)comfort and the development of sportswear as well as protective clothing. When considering the multifactorial nature of wear comfort, complementary data also examining the factors influencing it at the moment of the purchase (shop setting) and post-exercise, are necessary. This will potentially lead to a holistic model of wear comfort in an environment-human-clothing system.

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APPENDIX A

Loughborough University

STUDY TITLE

INFORMED CONSENT FORM

Taking Part	**Please initial box**
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 Ethics Approvals (Human Participants) Sub-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, have the right to withdraw from this study at any stage for any reason, and will not be required to explain my reasons for withdrawing.	☐
I agree to take part in this study. Taking part in the project will include being photographed.	☐
Use of Information	
I understand that all the personal information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others or for audit by regulatory authorities.	☐
I agree for the data I provide to be securely archived at the end of the project.	☐

Name of participant	[printed]	Signature	Date
Researcher	[printed]	Signature	Date

APPENDIX B

Name/Number ....

Health Screen Questionnaire for Study Volunteers

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.

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 or injury 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/chest pains	Yes ☐	No ☐
(i)	Problems with muscles, 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)	Problems with blood pressure	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.)

....

4. Smoking, physical activity and family history

(a)	Are you a current or recent (within the last six months) smoker?	Yes	☐	No	☐
(b)	Are you physically active (30 minutes of moderate intensity, physical activity on at least 3 days each week for at least 3 months)?	Yes	☐	No	☐
(c)	Has any, otherwise healthy, member of your family under the age of 35 died suddenly during or soon after exercise?	Yes	☐	No	☐

5. Allergy Information

(a)	Are you allergic to any food products?	Yes	☐	No	☐
(b)	Are you allergic to any medicines?	Yes	☐	No	☐
(c)	Are you allergic to plasters?	Yes	☐	No	☐
(d)	Are you allergic to latex?	Yes	☐	No	☐

If YES to any of the above, please provide additional information on the allergy

....

6. 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	☐

7. Are you currently involved in any other research studies at the University or elsewhere?

Yes ☐ No ☐

If yes, please provide details.

....

8. Please provide contact details of a suitable person for us to contact in the event of any incident or emergency.

Name ....

Telephone Number ....

Work ☐ Home ☐ Mobile ☐

Relationship to Participant ....

APPENDIX C

Project Title
Adult Participant Information Sheet

Name Main Investigator, University postal and email address and contact number
Names of all Other Investigators, University postal and email address and contact number

Please do not use personal addresses or mobile numbers as these pose a personal security risk. Project specific mobile numbers can be used.

Section A: Questions that should always be included on the Information Sheet:

What is the purpose of the study?

Please provide participants with a brief introduction to the study. This should be in terminology suitable for non-expert participants and take into consideration the age and nature of the intended participants. Information should cover the reasons for the study and what the investigators hope to achieve from the study.

Who is doing this research and why?

This should give an overview of who will be doing the research, who will be assisting and who the supervisors are. It should also give the details of the sponsor of and funding for the study, in the case of student research this should state "This study is part of a Student research project supported by Loughborough University."

Are there any exclusion criteria?

What will I be asked to do?

If participants are required to attend a number of different sessions please give details of what they will be required to do at each of the individual sessions. This should be a detailed step-by-step description of the requirements on them. If it is possible and appropriate please include picture or diagrams of equipment to help participants.

At the familiarisation session

At the first testing session

At the second testing session

etc

Once I take part, can I change my mind?

Suggested text: Yes. After you have read this information and asked any questions you may have we will ask you to complete an Informed Consent Form, however if at any time, before, during or after the sessions you wish to withdraw from the study please just contact the main investigator. You can withdraw at any time, for any reason and you will not be asked to explain your reasons for withdrawing.

Please adapt the following so that it is relevant to your project: However, once the results of the study are aggregated/published/dissertation has been submitted (expected to be by <date>), it will not be possible to withdraw your individual data from the research.

Will I be required to attend any sessions and where will these be?

How long will it take?

Please outline either the expected time requirement for each session or the total time required. This should include the expected amount of time any questionnaires, interviews or focus groups will take to complete.

What personal information will be required from me?

Are there any risks in participating?

Please give details of the possible risks of participating in the research. This should include the likelihood, severity and the expected time that this will effect participants for.

Will my taking part in this study be kept confidential?

Please outline the steps taken to ensure confidentiality and data security during collection, storage and analysis of data. This should also indicate how long the information will be kept for. Explicit clarification should be given for any studies which include video or audio recording and/or the collection and disposal of tissue samples.

I have some more questions; who should I contact?

What will happen to the results of the study?

What if I am not happy with how the research was conducted?

Suggested text:

If you are not happy with how the research was conducted, please contact Ms Jackie Green, the Secretary for the University's Ethics Approvals (Human Participants) Sub-Committee:

Ms J Green, Research Office, Hazlerigg Building, Loughborough University, Epinal Way, Loughborough, LE11 3TU. Tel: 01509 222423. Email: J.A.Green@lboro.ac.uk

The University also has a policy relating to Research Misconduct and Whistle Blowing which is available online at http://www.lboro.ac.uk/committees/ethics-approvals-human-participants/additionalinformation/codesofpractice/ . Please ensure that this link is included on the Participant Information Sheet.

Section B: Questions that you may wish to include on the Information Sheet, if relevant to your study:

Is there anything I need to do before the sessions?

This could be completed background questionnaires, food diaries or for participants to discuss the requirements with their family and GP.

Is there anything I need to bring with me?

This could be medication needed, specific equipment, their own packed lunch etc.

What type of clothing should I wear?

Is there anything specific your participants should wear to the sessions such as training clothes?

Who should I send the questionnaire back to?

What do I get for participating?

This can include any information that can be given back to the participant, for example health and fitness statistics, but also details of any payments or reimbursements. This can also include a statement on participants contributing to research, policy etc.

APPENDIX D

Comparisons between T-Shirt regions at each run conditions. Data from Laboratory study 5

Significance levels of comparison of local sweat absorption data after 10 MIN of running

10 MIN	COLLAR	SHOULDERS	CHEST LATERAL	CHESTMEDIAL	ABDOMEN MEDIAL	ABDOMEN LATERAL	LOWER END FRONT	UPPER BACK	MEDIAL MID BACK	LATERAL MID BACK	MEDIAL LOWER BACK	LATERAL LOWER BACK	LOWER END BACK	SLEEVE FRONT	SLEEVE BACK
COLLAR															
SHOULDERS						*		*	*	**	*				**
CHEST LATERAL									*	**					**
CHESTMEDIAL															
ABDOMEN MEDIAL						*	*		*	*			*		**
ABDOMEN LATERAL		*			*			*	*	*	*				**
LOWER END FRONT					*			*	*	*	*			*	**
UPPER BACK		*				*	*					*	*		
MEDIAL MID BACK		*	*		*	*		*				**	*		
LATERAL MID BACK		**	**		*	**	**					**	**		
MEDIAL LOWER BACK		*				*	*					**	*		
LATERAL LOWER BACK								*	**	**	**				**
LOWER END BACK					*			*	*	**	*			*	**
SLEEVE FRONT							*						*		*
SLEEVE BACK		**	**		**	**	**						**	***	*

Data uncorrected for multiple comparisons: p ≤ 0.05 *   p ≤ 0.01 **   p ≤ 0.001 ***

Data corrected (Bonferroni) for multiple comparisons: p ≤ 0.05 †   p ≤ 0.01 ††   p ≤ 0.001 †††

Significance levels of comparison of local sweat absorption data after 20 MIN of running

20 MIN	COLLAR	SHOULDERS	CHEST LATERAL	CHESTMEDIAL	ABDOMEN MEDIAL	ABDOMEN LATERAL	LOWER END FRONT	UPPER BACK	MEDIAL MID BACK	LATERAL MID BACK	MEDIAL LOWER BACK	LATERAL LOWER BACK	LOWER END BACK	SLEEVE FRONT	SLEEVE BACK
COLLAR		**	**		**	**	**			*		**	**	**	**
SHOULDERS	**			*		**		**	*** †	*	*		***		*
CHEST LATERAL	**			*				**	***	*	*		*		
CHESTMEDIAL		*	*		*	**	*					*	**	*	*
ABDOMEN MEDIAL	**			*				**	*** †	** †	*		*		*
ABDOMEN LATERAL	**	**		**				***	***	**	**	*	**	**	**
LOWER END FRONT	**			*				**	***		**				
UPPER BACK		**	**		**	*** †	**		**			*** †	*** †	**	**
MEDIAL MID BACK		*** †	***		*** †	*** †	***	**		***	***	*** ††	*** ††	*** †	*** ††
LATERAL MID BACK	*	*	*		**	**			***			**	**	**	
MEDIAL LOWER BACK		*	*		*	**	*		***			*	*	*	
LATERAL LOWER BACK	**			*		*		*** †	*** ††	**	*		*		*
LOWER END BACK	**	***	*	**	*	**		*** †	*** ††	**	**	*		*	***
SLEEVE FRONT	**			*		*		**	*** †	**	*		*		*
SLEEVE BACK	**	*		*	*	**		**	*** ††			*	***	*	

Data uncorrected for multiple comparisons: p ≤ 0.05 *   p ≤ 0.01 **   p ≤ 0.001 ***

Data corrected (Bonferroni) for multiple comparisons: p ≤ 0.05 †   p ≤ 0.01 ††   p ≤ 0.001 †††

Significance levels of comparison of local sweat absorption data after 30 MIN of running

30 MIN	COLLAR	SHOULDERS	CHEST LATERAL	CHESTMEDIAL	ABDOMEN MEDIAL	ABDOMEN LATERAL	LOWER END FRONT	UPPER BACK	MEDIAL MID BACK	LATERAL MID BACK	MEDIAL LOWER BACK	LATERAL LOWER BACK	LOWER END BACK	SLEEVE FRONT	SLEEVE BACK
COLLAR		**	**		*	**	**					**	**	**	**
SHOULDERS	**			**		**	**	***	***	*	*		**		
CHEST LATERAL	**			**		*	*	*	***	*	*		*		
CHESTMEDIAL		**	**		*	**	**					*	**	**	*
ABDOMEN MEDIAL	*			*					**						
ABDOMEN LATERAL	**	**	*	**				*** †	*** †	**	**	*			**
LOWER END FRONT	**	**	*	**				***	*** †	**	***	*		**	**
UPPER BACK		***	*			*** †	***		*			*** †	***	**	**
MEDIAL MID BACK		***	***		**	*** †	*** †	*		*** †	**	*** †	*** †	***	***
LATERAL MID BACK		*	*			**	**		*** †			**	**	**	**
MEDIAL LOWER BACK		*	*			**	***		**		***	*** †	***	**	**
LATERAL LOWER BACK	**			*		*	*	*** †	*** †	**	*** †		*		
LOWER END BACK	**	**	*	**				***	*** †	**	***	*		**	**
SLEEVE FRONT	**			**			**	**	***	**	**		**		*
SLEEVE BACK	**			*		**	**	**	***	**	**		**	*	

Data uncorrected for multiple comparisons: p ≤ 0.05 *   p ≤ 0.01 **   p ≤ 0.001 ***

Data corrected (Bonferroni) for multiple comparisons: p ≤ 0.05 †   p ≤ 0.01 ††   p ≤ 0.001 †††

Significance levels of comparison of local sweat absorption data after 40 MIN of running

40 MIN	COLLAR	SHOULDERS	CHEST LATERAL	CHESTMEDIAL	ABDOMEN MEDIAL	ABDOMEN LATERAL	LOWER END FRONT	UPPER BACK	MEDIAL MID BACK	LATERAL MID BACK	MEDIAL LOWER BACK	LATERAL LOWER BACK	LOWER END BACK	SLEEVE FRONT	SLEEVE BACK
COLLAR		***	**			*** †	*** †					*	*** †	***	**
SHOULDERS	***			**		***	***	*** †	*** †	*	**		**	*	
CHEST LATERAL	**			*		**	**	*	***	*	**		*	*	
CHESTMEDIAL		**	*			***	***					*	***	**	**
ABDOMEN MEDIAL						*	*						*		
ABDOMEN LATERAL	*** †	***	**	***	**		*	*** †††	*** †††	*** †	*** ††	*		**	***
LOWER END FRONT	*** †	***	**	***	*	*		*** †††	*** †††	***	*** †	*		**	*** †
UPPER BACK		*** †	*			*** †††	*** †††		*			*	*** ††	*** †	***
MEDIAL MID BACK		*** †	***			*** †††	*** †††	*		**	*	*** ††	*** †††	*** ††	*** †
LATERAL MID BACK		*	*			*** †	***		**		**	*** †	***	**	** ††
MEDIAL LOWER BACK		**	**			*** ††	*** †		*	**		*** ††	*** ††	*** †	*** ††
LATERAL LOWER BACK	*			*		*	*	**	*** ††	*** †	*** ††		**		
LOWER END BACK	*** †	**	*	**	*			*** ††	*** †††	***	*** ††	**			**
SLEEVE FRONT	***	*	*	**		**	**	*** †	*** †††	**	*** †				**
SLEEVE BACK	**			**		*** †	***	*** †	*** ††	**	*** ††		**		**

Data uncorrected for multiple comparisons: p ≤ 0.05 *   p ≤ 0.01 **   p ≤ 0.001 ***

Data corrected (Bonferroni) for multiple comparisons: p ≤ 0.05 †   p ≤ 0.01 ††   p ≤ 0.001 †††

Significance levels of comparison of local sweat absorption data after 50 MIN of running

50 MIN	COLLAR	SHOULDERS	CHEST LATERAL	CHESTMEDIAL	ABDOMEN MEDIAL	ABDOMEN LATERAL	LOWER END FRONT	UPPER BACK	MEDIAL MID BACK	LATERAL MID BACK	MEDIAL LOWER BACK	LATERAL LOWER BACK	LOWER END BACK	SLEEVE FRONT	SLEEVE BACK
COLLAR		**	*		*	***	***					*	**	**	*
SHOULDERS	**			**		*	**	*	*** ††	*	*** ††			*	
CHEST LATERAL	*		*			**	**		***		***		*	*	
CHESTMEDIAL		**	*		*	**	***					*	**	**	*
ABDOMEN MEDIAL	*			*	*	*		**	**	*					
ABDOMEN LATERAL	***	*	**	**	*			*	*** ††	***	*** ††	*			**
LOWER END FRONT	***	**	**	***	*			**	*** ††	***	*** ††	*		*	***
UPPER BACK		*				*	**	*					**	**	
MEDIAL MID BACK		*** ††	***		**	*** ††	*** ††	*		**		***	*** †	*** †††	*** †††
LATERAL MID BACK		*				***	***		**			**	**	***	**
MEDIAL LOWER BACK		*** ††	***		*	*** ††	*** ††					*** †	*** †	*** ††	*** ††
LATERAL LOWER BACK		*		*		*	*		***	**	*** †		*		
LOWER END BACK	**		*	**				**	*** †	**	*** †	*			*
SLEEVE FRONT	**	*	*	**			*	**	*** †††	***	*** ††				**
SLEEVE BACK	*			*		**	***		*** †††	**	*** ††		*	**	

Data uncorrected for multiple comparisons: $p \leq 0.05$ * $p \leq 0.01$ ** $p \leq 0.001$ ***

Data corrected (Bonferroni) for multiple comparisons: $p \leq 0.05$ † $p \leq 0.01$ †† $p \leq 0.001$ †††

APPENDIX E

Original article

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Human wetness perception in relation to textile water absorption parameters under static skin contact

Margherita Raccuglia, Simon Hodder and George Havenith

Abstract

Skin wetness perception (WP) greatly affects thermal and sensorial discomfort in clothing and as such is of great interest to the clothing industry. Following neurophysiological studies of WP, this study looks at textile parameters affecting WP. Twenty-four fabrics varying in thickness, fiber type and absorption capacity were studied. Using 12 participants (males/females), the WP induced was studied in four wetness states: 1. Dry; 2. absolute (ABS), all having the same absolute water content of 2400 μL per sample (=0.24 $\mu L\,mm^{-2}$); 3. 100REL, saturated with water to their individual absorption capacity; 4. 50REL, to 50% of the value in 3. As total absorption capacity was highly correlated ($r = 0.99$) to fabric thickness, conditions 3 and 4 were equivalent to having the same water content per volume of textile, i.e. 0.8 and 0.4 $\mu L\,mm^{-3}$, respectively. Samples were applied to the upper back statically to minimize the contribution of surface roughness/friction. WP was highly correlated to drop in skin temperature induced by the wet fabric, and increased with application pressure of the fabric. No effect of fiber type was observed. In REL, with equal $\mu L\,mm^{-3}$, WP showed a positive correlation to total fabric water-content-per-area ($\mu L\,mm^{-2}$), and thus also to thickness, given the correlation between the latter two, with saturation above 1.5 $\mu L\,mm^{-2}$. In ABS, on the other hand, with equal $\mu L\,mm^{-2}$, and thus with relative water content (μL mm $\mu L\,mm^{-3}$) inversely proportional to thickness, WP was also inversely proportional to thickness. Thus WP showed opposing responses depending on the wetting type, indicating that the methodology of manipulating water content should be selected in relation to the product end-use.

Keywords

wetness perception, fabric water content, absorption capacity, fabric thickness, fabric fiber type, fabric wet weight

The haptic perception of wetness while wearing clothing represents one of the most critical factors contributing to thermal and sensorial discomfort during wear.[1–3] It has been acknowledged that, despite the ability to perceive wetness, the human skin is not provided with specific hygro-receptors.[4] Therefore, the study of human wetness sensation has attracted many researchers from multiple disciplines.[3,5–8] Regarding the modality in which humans perceive moisture and humidity, recently it has been proposed that the perception of wetness is based on a multimodal integration of thermal and mechanical inputs occurring at the skin, when it is wet.[8,9]

With regard to textile materials, which often come in contact with the human body, the level of wetness is not an intrinsic property of the material in itself, such as texture or temperature, but is defined by the combined effect of the amount of liquid present in the fabric (e.g. sweat rate, rain) and on the ability of the fabric to absorb moisture, i.e. hygroscopicity. The majority of the studies available that have investigated the mechanisms underlying the ability to perceive wetness have often neglected the contribution of fabric properties and our knowledge on how these modulate wetness perception is still limited. On the other hand, the

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APPENDIX F

Original article

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SAGE

Human wetness perception of fabrics under dynamic skin contact

Margherita Raccuglia[1], Kolby Pistak[1], Christian Heyde[2], Jianguo Qu[3], Ningtao Mao[3], Simon Hodder[1] and George Havenith[1]

Abstract

This experiment studied textile (surface texture, thickness) and non-textile (local skin temperature changes, stickiness sensation and fabric-to-skin pressure) parameters affecting skin wetness perception under dynamic interactions. Changes in fabric texture sensation between WET and DRY states and their effect on pleasantness were also studied. The surface texture of eight fabric samples, selected for their different structures, was determined from surface roughness measurements using the Kawabata Evaluation System. Sixteen participants assessed fabric wetness perception, at high pressure and low pressure conditions, stickiness, texture and pleasantness sensation on the ventral forearm. Differences in wetness perception ($p < 0.05$) were not determined by texture properties and/or texture sensation. Stickiness sensation and local skin temperature drop were determined as predictors of wetness perception ($r^2 = 0.89$), and although thickness did not correlate with wetness perception directly, when combined with stickiness sensation it provided a similar predictive power ($r^2 = 0.86$). Greater ($p < 0.05$) wetness perception responses at high pressure were observed compared with low pressure. Texture sensation affected pleasantness in DRY ($r^2 = 0.89$) and WET ($r^2 = 0.93$). In WET, pleasantness was significantly reduced ($p < 0.05$) compared to DRY, likely due to the concomitant increase in texture sensation ($p < 0.05$). In summary, under dynamic conditions, changes in stickiness sensation and wetness perception could not be attributed to fabric texture properties (i.e. surface roughness) measured by the Kawabata Evaluation System. In dynamic conditions thickness or skin temperature drop can predict fabric wetness perception only when including stickiness sensation data.

Keywords

wetness perception, fabric motion, stickiness, surface roughness, fabric texture, Kawabata, pleasantness

Whenever we increase our activity level and body heat content, sweat production causes moisture to build up on the skin. The human ability to perceive skin wetness causes tactile and thermal discomfort,[1] these driving behavioral thermoregulatory responses[2] that are aimed at maintaining homeostasis, ensuring health and survival.[3] In the absence of visual or auditory cues, skin wetness is perceived via learning processes[4] and through the central integration of thermal and mechanical stimuli occurring at the skin[5,6]

A large body of research has been focusing on the complex multisensory modality of wetness perception (WP) using fabrics.[7-10] For instance, Li,[11] in wear trials, and recently Raccuglia et al.,[12] in local body sensorial trials, highlighted the contribution of cold sensation to the perception of fabric moisture. Specifically, in both studies greater WP was observed in response to greater reduction in skin temperature, which in return was affected by fabric water content.

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