Applied Ergonomics 73 (2018) 33–41

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Clothing comfort during physical exercise – Determining the critical factors

Margherita Raccuglia[a], Benjamin Sales[a], Christian Heyde[b], George Havenith[a], Simon Hodder[a,*]

[a] Environmental Ergonomics Research Centre, Loughborough Design School, Loughborough University, Loughborough, UK
[b] Adidas FUTURE Sport Science, Herzogenaurach, Germany

ARTICLE INFO

Keywords:
Clothing comfort
Wetness perception
Stickiness sensation
Fabric contact area
Texture sensation

ABSTRACT

Clothing comfort is determined by multiple material and design factors. Wetness at the skin-clothing interface mainly impacts wear comfort. 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. Moreover, factors causing wear (dis)comfort during exercise were identified. 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. Therefore, fabric saturation percentage mainly affects stickiness sensation of wet fabrics, overruling the impact of fabric contact area and absolute sweat content. No overall model of wear discomfort across all data could be developed, however, 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.

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., 2014). 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

* Corresponding author.
E-mail address: s.hodder@lboro.ac.uk (S. Hodder).

https://doi.org/10.1016/j.apergo.2018.05.014
Received 22 November 2017; Received in revised form 21 April 2018; Accepted 27 May 2018

Nomenclature

ANOVA	analysis of variance
Contact-SA	contact surface area
GSL	gross sweat loss
HIGH	high contact surface area
HR	heart rate
LOW	low contact surface area
MEDIUM	medium contact surface area
Pes	polyester
Sample ABS	sample moisture absorption capacity
$SWEAT_{AB}$	amount of sweat absorbed in the garment
T_{core}	core temperature

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 roles of fabric thickness (static skin contact) and surface texture (dynamic skin contact) on skin wetness perception was investigated (Raccuglia et al. 2016a, 2016b, 2017a, 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, 2016b). Specifically, when applying the same relative to volume water content (mL·mm^{-3}; same saturation percentage) thicker fabrics were perceived wetter than the thinner ones. Conversely, when adding the same absolute water amount (mL·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. 2017a, 2017c), 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, 2017c). 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.

2. Method

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

Table 1
Experimental fabrics/garment specifications.

Fabrics/Garment	Fibre type	Thickness (mm)	Fabric Mass (gm^2)	Structure	Denier count	Sample Contact-SA (%)	Sample ABS (gm^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.