International Journal of Industrial Ergonomics 42 (2012) 212–218

Contents lists available at SciVerse ScienceDirect

International Journal of Industrial Ergonomics

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

Heat loss and moisture retention variations of boot membranes and sock fabrics: A foot manikin study

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ARTICLE INFO

Article history:
Received 16 May 2011
Received in revised form
25 November 2011
Accepted 20 January 2012
Available online 20 February 2012

Keywords:
Heat loss
Moisture retention
Hiking
Footwear
Marching
Sock
Fabric
Boot
Membrane
Manikin

ABSTRACT

Heat loss and moisture retention properties of footwear were characterized using a walking thermal manikin foot. The same type of military boot was equipped with different membranes: (i) GORE TEX with IQ TEX, (ii) halve OUTDRY, (iii) full OUTDRY, and (iv) OUTDRY with IQ TEX. In a separate experiment a single boot type was used to evaluate four different sock fabrics: (i) wool/polypropylene, (ii) polypropylene, (iii) polypropylene/polyamide, and (iv) wool/polyamide. Both boot membranes and sock fabrics were assessed under three conditions: (i) standstill no sweating, (ii) walking no sweating, and (iii) walking and sweating. The walking rate was set at 15 step min^{-1} and the sweat rates were 9 g h^{-1} and 12 g h^{-1}, for boot membrane and sock fabric measurements, respectively. Moisture retention was assessed by weighing the footwear components before and after each measurement. GORE TEX with IQ TEX resulted in a higher heat loss during walking without sweating compared to the other membranes ($p = 0.017$). GORE TEX with IQ TEX retained more moisture in the sock compared to the other membranes ($p < 0.001$) but also retained more moisture in the inlay sole compared to halve OUTDRY ($p = 0.015$). No differences in heat loss were found among sock fabrics, while wool/polyamide retained more moisture compared to polypropylene/polyamide ($p = 0.036$). Furthermore, a moisture vapour transmission rate of 61.2 ± 6.6 g m^{-2} h^{-1} was calculated for all sweating conditions. Finally, the measurements suggest that no pumping effect takes place in the measured footwear under the present conditions.

Relevance to industry: Understanding heat loss and moisture retention of footwear is necessary for optimization of footwear for blister incidence and (thermal) comfort.

1. Introduction

Friction blisters on the foot are among the most occurring injuries for hikers (Crouse and Josephs, 1993; Gardner and Hill, 2002; Twombly and Schussman, 1995) and infantry soldiers (Knapik et al., 1992, 1997; Reynolds et al., 1999). Friction between the skin and sock, also referred to as shear forces, are responsible for the aetiology of friction blisters (Naylor, 1955; Sulzberger et al., 1966). These shear forces increase with increased skin hydration as well as increased moisture content of the textile in contact with the skin (Elsner et al., 1990; Gerhardt et al., 2008; Gwosdow et al., 1986; Kenins, 1994; Nacht et al., 1981; Sulzberger et al., 1966). Therefore, further studies have focussed on the effect of sock fabric on blister incidence (Knapik et al., 1996; Van Tiggelen et al., 2009) and physiological parameters at the level of the foot related to blister incidence, e.g., skin hydration and skin friction (Bogerd et al., in press, 2011). These studies indicate that sock fabric affect blister incidence differently. However, the studies identify different fabric blends as optimal. Two studies identified optimal blends as not having wool or cotton in direct contact with the skin (Knapik et al., 1996; Van Tiggelen et al., 2009), whereas a wool blend was found to result in less hydrated skin for foot sites other than the plantar foot after a few hours of walking (Bogerd et al., in press). However, the aforementioned studies did not consider the moisture retention in footwear in detail. Previously, moisture retention of footwear components has been evaluated for cold weather boots during measurements in a simulated cold environments (Kuklane and Holmér, 1998; Kuklane et al., 1999b).

Few publications report on comfort aspects of socks, compared to clothing comfort as consumers indicate comfort as an important decisive factor (Alcántara et al., 2005a; b). Only three studies evaluate perception parameters, e.g., temperature and comfort, of socks during use (Bertaux et al., 2010; Bogerd et al., in press; Herring and Richie, 1990). Due to differences in evaluated fabrics, and applied protocols, it is difficult to find an overall pattern (Table 1). These three studies have all used human participants to evaluate different

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0169-8141/$ – see front matter
doi:10.1016/j.ergon.2012.01.001

sock fabrics. Contrary to measurements on human participants which are affected by inter-individual and intra-individual variations in sensitivity, thermal manikins can give an reliable measure of be heat transfer and are therefore useful in predicting temperature and comfort perception of participants, as shown for a thermal head manikin (Bogerd and Brühwiler, 2011; Brühwiler et al., 2004; Liu et al., 1999) and whole body thermal manikins (Nilsson and Holmér, 2003). Several foot manikins are described in the literature (Babič et al., 2008; Bergquist and Holmér, 1997; Schols et al., 2004) and showed that heat loss measured with a thermal foot manikin follows a similar dynamic as temperature perception by participants in a cold environment (Kuklane et al., 1999a). So far, several studies have employed these thermal foot manikins for assessing footwear properties in cold conditions (e.g., Kuklane et al., 1999a; Kuklane and Holmér, 1998; Kuklane et al., 1999b, 2009), but neutral to warm conditions have not yet been studied in detail using such methods.

Marching and hiking is abundantly practised during neutral and warm conditions, with reported sweat rates ranging between 447 g m^{-2} h^{-1} and 391 g m^{-2} h^{-1} (Bogerd et al., 2011; Fogarty et al., 2007; Taylor et al., 2006). It remains unclear how different footwear affects heat loss and moisture retention in neutral and warm conditions. Therefore, the present study aims at quantifying heat loss variations and moisture retention of footwear in two sub-studies in which (i) different water-proofing solutions are assessed, and (ii) different sock fabrics are evaluated.

2. Methods

2.1. Foot manikin

The commercially-available walking, sweating, thermal foot manikin (UCS, Vrhnika, Slovenia) is displayed in Fig. 1 and described in detail elsewhere (Babič et al., 2008). In brief, the foot manikin is made of 13 metal shell-parts, each equipped with temperature sensors, heating elements, and perspiration nozzles. The foot manikin represents a right foot and 32 perspiration nozzles are distributed evenly over the entire foot manikin.

The main differences between the foot manikin employed in the present study and the manikin described by Babič et al. (2008) were: (i) the present manikin is hollow, aside from support structures, heaters, electronics, and moisture tubes; (ii) more of the calf was included in the present foot manikin, entailing also more heated sections; (iii) the manikin shape is based on the average of approximately three thousand Swiss army recruits with a boot size of EU 43; (iv) The foot manikin was modified by adding individual control of the moisture emitted from each perspiration nozzle, similar to the system used in other manikins in our laboratory (Brühwiler, 2003; Psikuta et al., 2008). In the modified perspiration system, each nozzle was supplied by a separate tube, having its own electronic flow control. The tubes were fed from a reservoir placed above the set-up, so that gravity created the pressure allowing the distilled water to flow. A separate computer controlled the moisture dosage to each nozzle by regulating the opening time and frequency of the corresponding valve. The moisture flow for each nozzle was (individually) calibrated.

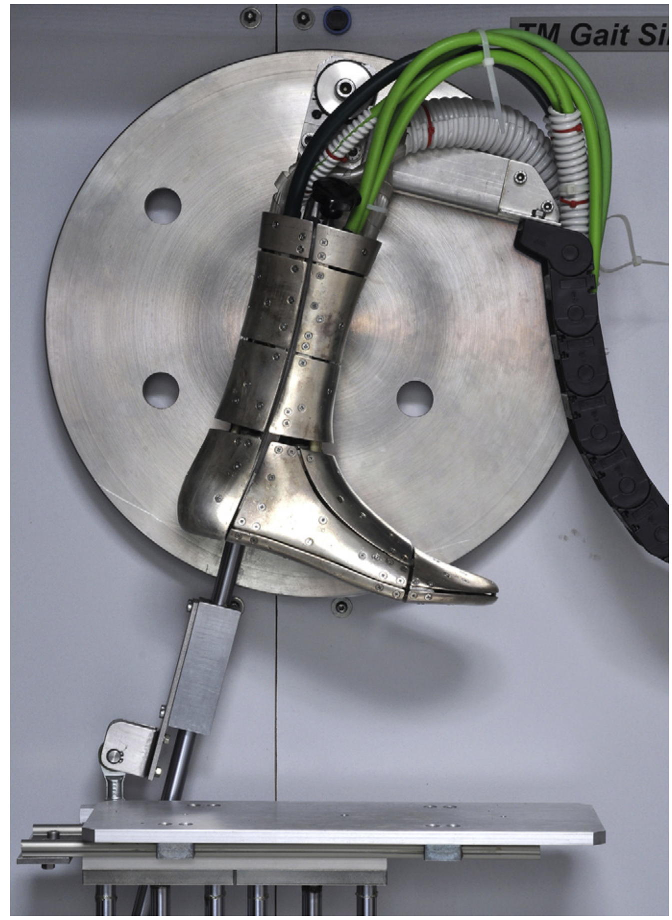

Fig. 1. The foot manikin and gait-simulator.

The foot manikin simulates walking via counter-clockwise rotation of the disk on which it is mounted. A plane mounted on rods exerts a damped upward force and simulated the walking surface. The net force on the foot manikin was set to 25 kg while walking, with a variable walking rate specified under Section 2.3. During measurements, air exchange between the foot manikin and climate chamber was limited, occurring through ventilation openings in the container encapsulating the foot manikin system. For this reason, air temperature (21.2 ± 0.2 °C) and relative humidity (42.6 ± 0.9%) were continually measured inside the cabinet and the entire system was placed in a climate chamber.

Table 1
Significant differences in perception of sock fabrics from previous studies.

Reference	n	Mode	Technique	Sock fabrics		Sig. differences in perception[a]	
				a	b	Temperature	Dampness
Herring and Richie, 1990	35	Long Distance Running	Field	CO	AC	a = Cooler	a = More Damp
Bertaux et al., 2010[b]	6	40 min of Running	Laboratory	CO/PA	PP	a = Cooler	a = More Damp
				CO/PA	PA/PTFE		a = More Damp
				PA/PTFE	PP		a = Less Damp
Bogerd et al., in press	35	Daily Military Usages inc. March	Field	WO/PP/PA	PP	a = Cooler	a = Less Damp

AC = Acrylic, CO = cotton, EL = elastane, PA = Polyamide, PE = polyester, PTFE = polytetrafluoroethylene, PP = polypropylene, and WO = wool.
[a] Significance is considered as $p < 0.05$.
[b] This study evaluated perception on different regions of the foot, which are not given in this table.