Development and Validation of an Empirical Equation to Predict Wet Fabric Skin Surface Temperature of Thermal Manikins

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Abstract: Thermal manikins are useful tools to study clothing comfort and environmental ergonomics. The simulation of sweating can be achieved by putting a highly wicking stretchable knit fabric "skin" on top of the manikin. However, the addition of such a fabric skin makes it difficult to accurately measure the skin surface temperature. Moreover, it takes considerable amount of time to measure the fabric skin surface temperature at each test. At present the attachment of temperature sensors to the wet fabric skin is still a challenge. The distance of the sensors to the fabric skin could significantly influence the temperature and relative humidity values of the wet skin surface. Hence, we conducted an intensive skin study on a dry thermal manikin to investigate the relationships among the nude manikin surface temperature, heat losses and the fabric skin surface temperature. An empirical equation was developed and validated on the thermal manikin 'Tore' at Lund University. The empirical equation at an ambient temperature 34.0 ºC is T_{sk}=34.00-0.0103HL. This equation can be used to enhance the prediction accuracy of wet fabric skin surface temperature and the calculation of clothing evaporative resistance.

Keywords: Fabric skin, thermal manikin, skin surface temperature, isothermal, empirical equation, clothing ensemble.

1. Introduction

Thermal manikins are widely used in governmental, industrial and academic research institutes to evaluate the environmental and occupational protective capabilities of clothing, footwear, handwear and even headgear [1]. It is well documented that thermal manikins are one of the most ideal instruments for measuring the thermal and evaporative resistances of clothing ensembles [2-4]. Although thermal manikins have served research and development purposes for about 70 years [3], the simulation of human sweating in thermal manikins is still a great challenge.

Our human body has 3 to 4 million eccrine sweat glands, with an average distribution of 150 to 340 per square centimetre [5]. They are mostly found in numerous quantities on the palms and soles and then, in decreasing order, on the head, trunk, and extremities. The specific function of sweat glands is to secrete water upon the skin surface so that it can cool the human skin when it evaporates. Man can perspire as much as several litres per hour and 10 litres per day [6]. Sweating is the most important effector function to reduce thermal strain of humans who are working in a hot environment.

Currently, there are three major approaches to sweating simulations in thermal manikins used worldwide [7-9]: pre-wetted high wicking fabric covering a dry thermal manikin, thermal manikins with pumps to regulate the water supply through 'sweating' glands to a wicking knit fabric, and sweating fabric manikins based on a water filled body covered with waterproof but permeable fabric, such as Gore-tex fabrics.

The embedded heating wires under the thermal manikin surface heat each segment to a set temperature. The wet skin test is conducted to determine the clothing evaporative resistance. As it is the manikin's skin temperature that is controlled, and not the wet skin, the evaporative cooling of the wet skin layer may generate a temperature difference between the wet skin surface and the controlled nude manikin surface. It is anticipated that this temperature difference is related to the overall evaporative heat loss of the manikin (and in non iso-thermal ambient conditions on the total heat loss). To some extent, the accuracy of 'measurement' of the wet skin surface temperature determines the accuracy of evaporative resistance of clothing ensembles. However, no data have been published on putting temperature sensors on the wet skin surface to accurately measure the skin surface temperature.

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Informally, various labs have reported attempts estimating skin temperature correction factors (Redortier, Havenith, Ueno, Kuklane, Burke; personal communications at ICEE 2007), but with limited success. Havenith (personal communication) studied this phenomenon using an infra-red camera on a thermal manikin 'Newton' [10] to measure surface temperatures and developed a prediction equation, which was not published either. Thus it was deemed useful to perform a study to measure wet skin surface temperatures and develop a series of skin temperature prediction equations relating the wet surface temperature to the manikin nude surface temperature and the total heat loss. Ideally, with such skin equations, we can predict the wet skin surface temperature without even using temperature sensors, avoiding a lot of technical issues. Moreover, such skin set equations can also be expected to predict the skin surface temperature for the wet skin with clothing ensembles worn on top.

In this study, a well fitted pre-wetted knit fabric skin was placed on top of the dry heated thermal manikin 'Tore' to simulate a wetted skin by sweating. The pre-wetted skin surface temperatures were measured on an undressed manikin by 18 digital temperature and relative humidity integrated sensors at an isothermal condition of 34.0 ºC. A correction equation for the prediction of skin's outer surface temperatures was developed based on the skin's inner surface temperatures measured. Finally, an empirical equation for the skin surface temperature prediction was developed and validated while the manikin was dressed with four different functional clothing ensembles.

2. Methods

2.1 Thermal manikin

A Swedish 17-segment thermal manikin 'Tore' was used in this study (Figure 1). 'Tore' is made of plastic foam with a metal frame inside to support body parts and for joints [11]. It is the size of an average Swedish male of 1980s. Its height is 170 cm, chest and waist circumferences are 94 and 88 cm respectively, with a total heated body area of 1.774 m^2. The manikin surface temperature can be controlled independently within ±0.5 ºC, and the total heat input required to achieve this was accurately measured within ± 2 %.

The heat input is a direct measure of the heat loss from the manikin [12]. When put in isothermal conditions ($T_{sk} = T_a = T_r$) this directly reflects the evaporative heat loss, as radiative and convective gradients will be zero.

Figure 1 The thermal manikin 'Tore' in the climatic chamber.

2.2 Skin layer

A knit cotton fabric skin was used in this study. The skin was specially designed for the thermal manikin 'Tore' to fit it tight. Before each wet test, the cotton skin was rinsed in a washing machine (Electrolux W3015H, Sweden) for 4 minutes and then centrifuged for 4 seconds to ensure no water would drip from the skin.

2.3 Test conditions

The manikin surface temperature was set to 34.0 ºC. All skin tests were conducted at an isothermal condition where the ambient temperature was 34.0 ºC. Three platinum air temperature sensors set at the height of 0.1, 1.1 and 1.7 m were used to record the ambient temperatures. The air velocity was controlled at 0.33±0.09 m/s for all tests. The air inlets in the climatic chamber are on the ceiling and an air outlet is on the