Development of Empirical Equations to Predict Sweating Skin Surface Temperature for Thermal Manikins in Warm Environments.

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DEVELOPMENT OF EMPIRICAL EQUATIONS TO PREDICT SWEATING SKIN SURFACE TEMPERATURE FOR THERMAL MANIKINS IN WARM ENVIRONMENTS

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INTRODUCTON

Clothing evaporative resistance determines how much sweat could be evaporated through clothing ensembles to the environment. As one of the most important physical parameters for a garment, it is widely used as the basic input in thermal comfort models. Currently, there is only one international standard regarding to how to measure clothing evaporative resistance using a thermal manikin [1]. Based on this standard, clothing evaporative resistance can be calculated by two options: heat loss method and mass loss method. Since current manikin technology could detect the exact amount of heat loss accurately, also, the mass loss rate from the sweating skin can be measured by a high accuracy weighing scale. Therefore, the calculation accuracy on water vapour gradient between the wet skin surface and the ambient directly determines the calculation accuracy of clothing evaporative resistance.

The prevailing method to calculate water vapor resistance of the sweating skin assumes the relative humidity on the wet skin surface is 100 %. According to Antonio's equation, the measurement accuracy on sweating skin surface temperature directly determines the accuracy of clothing water vapour resistance. However, for most of the manikins worldwide, there is no feedback between the fabric skin surface and the manikin regulation system, i.e., the wet fabric skin surface temperature is not controlled by the regulating system. Therefore, the calculation on clothing evaporative resistance in various laboratories [2-4] is based on the manikin surface temperature rather than the sweating fabric skin surface temperature. Obviously, this is not correct. Wang et al. [5] investigated the calculations of evaporative resistance based on these two surface temperatures and found that an error of up to 35.9 % could be introduced by the temperature difference. They [6] developed an empirical equation to predict the sweating skin surface temperature for thermal manikins at 34 ^{o}C and this equation was successfully validated by adding four functional clothing ensembles on top of the sweating fabric skin. Recently, this empirical equation was further developed and a universal equation was presented and also validated [7]. This universal equation can be used to predict the wet fabric skin surface temperature on most of thermal manikins at a testing temperature range of 25 to 34 ^{o}C. Obviously, all those measurements were performed with the same fabric skin. As a result, there is still a gap in the effect of different fabric skins on the predicted wet skin temperature.

The main aim of this paper is to investigate the effect of difference fabric skins on the predicted sweating skin surface temperature. Also, two empirical equations were developed and compared. Finally, the possibility of integrating those two empirical equations to one equation was also discussed.

METHODS

Thermal manikin

A 17-segment dry heated thermal manikin ‘Tore’ was used in this study. This manikin is made up of plastic foam with a metal frame inside to support the body. The total surface area is 1.774 m^2 and weighs 30 kg. The whole manikin was placed in a controllable climatic chamber.

Fabric skins

A knit cotton fabric skin and a Gore-tex fabric skin were used. Those two fabric skins were specially made to fit our manikin. The areal weight of the Gore-tex fabric skin and the knit cotton fabric skin are 241 and 228 g/m^2, respectively. The cotton fabric skin was rinsed in a washing machine (Electrolux W3015H, Sweden) and centrifuged for 4 s to ensure no water was dripped during the test period. This cotton fabric skin was covered on top of the Gore-tex skin over the thermal manikin to simulate sensible sweating, while it was worn under the Gore-tex fabric skin to simulate senseless sweating, two example thermal manikins using such sweating methods are SAM and Coppelius [8, 9]. The fabric skins only cover 12 segments on the thermal manikin, except the head, hands and feet.

Test conditions

Six temperature sensors (SHT75, Sensirion Inc., Switzerland, accuracy: ±0.3 ^oC) were attached on six sites of the fabric skin outer surface (chest, upper arm, stomach, back, thigh, and calf) by using white thread rings (Resårband Gummilitze Elastic Braid, Sweden). For each skin combination, totally twelve tests were performed at three different ambient temperatures: 34, 25 and 20 ^oC. These three temperature levels could avoid moisture accumulation on the fabric skin outer surface due to observed dew points are always lower than those ambient temperatures. As a result, the effect of accumulation on the observed fabric skin temperature can be neglected. The air velocity was maintained at 0.33±0.09 m/s.

RESULTS

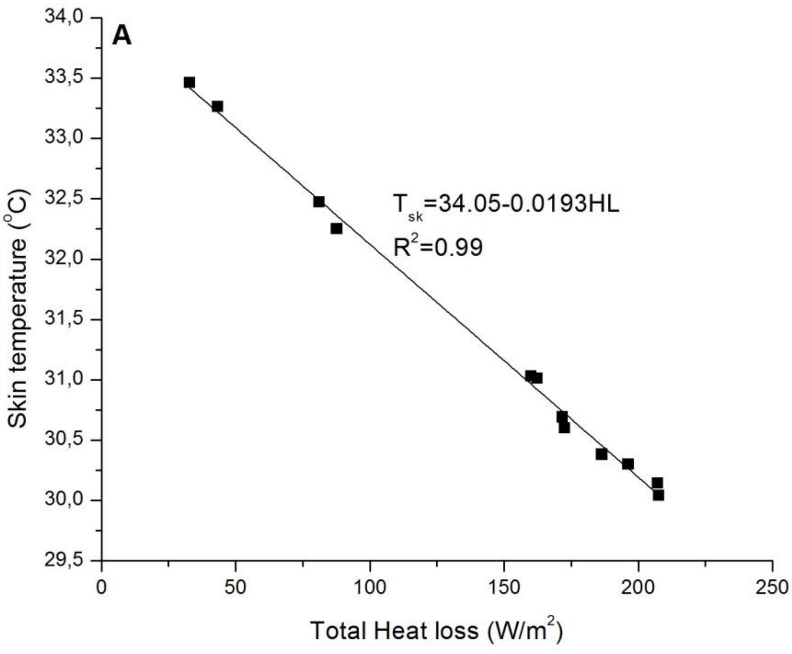
The total heat loss and averaged skin surface temperature of the sweating area were calculated for each skin combination. The total heat loss from the thermal manikin ranges from 32.9 to 242.4 W/m^2. Also, the averaged fabric skin temperature ranges from 29.9 to 33.6 ^oC. Two scatter charts were plotted for those two skin combinations. The linear regression lines were also drawn using Origin v.8.0 (OriginLab Corporation, USA). The results are displayed in Figure 1. The empirical equations for G+C and C+G skin combinations are expressed as follows

T_{sk}=34.05-0.0193HL

T_{sk}=34.63-0.0178HL

where, T_{sk} is the mean fabric skin surface temperature, ^{o}C; HL is the total heat loss from the thermal manikin.

It can be deduced from Figure 1 that the G+C fabric skin combination has greater influence on the skin surface temperature than the C+G fabric skin combination. This is because the outer Gore-tex fabric skin layer in the combination C+G constraints the moisture transfer to the environment due to its limited pore size of the laminated membrane. Therefore, less evaporation makes the mean skin surface temperature greater than the G+C combination at the same test condition. The findings are similar to the sweating case on a human body. For our body, sweating glands only release sensible sweat due to exercise, or environmental factors. However, insensible sweat continuously evaporates from the human body under all conditions [10].



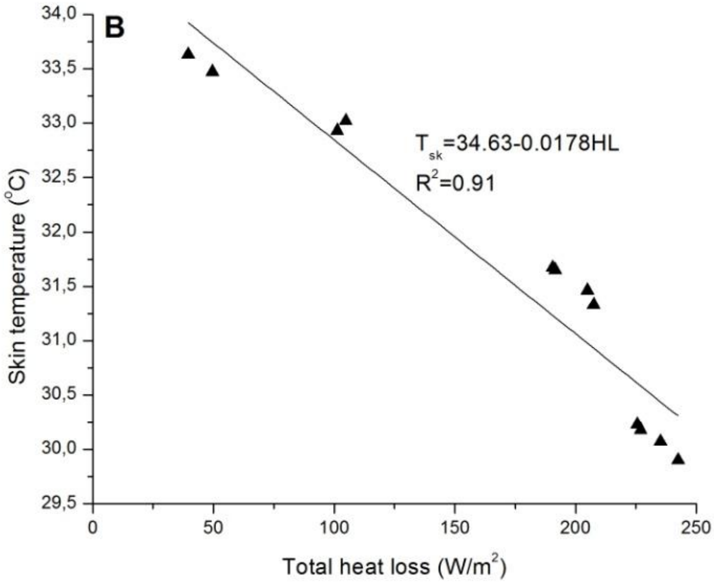


Figure 1 Empirical equation for predicting sweating fabric skin temperature. A: Gore-tex fabric skin inside+ cotton fabric skin combination outside (G+C); B: Cotton fabric skin inside + Gore-tex fabric skin combination outside (C+G).

Furthermore, we can also easily find that the outer fabric surface temperatures in C+G skin combination are always greater than that those in G+C skin combination. The observed amount of sweating in the C+G skin combination ranges from 150 to 348 g/h. Although the sweating rate of the C+G skin combination is lower than that in the G+C combination (156~378 g/h), the values are still much greater than the real case on a human body. On the other hand, for thermal manikins such as 'Walter' and 'Coppelius', the amount of senseless sweating per hour reported in previous studies [9, 11-13] is also much greater than the value on a human body (25 g/h [14]). Therefore, the simulation of senseless sweating on a thermal manikin using a piece of waterproof but permeable fabric is questionable.

Finally, by comparing those two empirical equations for different skin combinations, we suggest that using different empirical equations for different fabric skin combinations. Otherwise, the predicted fabric skin temperature may not be in an acceptable range (±0.5 ^{o}C).

CONCLUSIONS

In this study, the effect of different skin combinations on the predicted sweating fabric skin temperature was examined. It was found that the Gore-tex skin as an outer layer could limit sweat evaporation to the environment and the predicted fabric skin temperature on the thermal manikin is always greater than that in the G+C skin combination. Also, using current available waterproof but permeable fabric skin to simulate senseless sweating is questionable. Moreover, those equations are not validated on the thermal manikin. The prediction accuracy is still not clear either. Therefore, further studies on validation of those equations on a manikin are needed, however.

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