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THERMOREGULATORY MANIKINS ARE DESIRABLE FOR EVALUATIONS OF INTELLIGENT CLOTHING AND SMART TEXTILES

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INTRODUCTION

Thermal manikins have been used to measure thermal properties of clothing. The use of thermal manikins has made a step forward in terms of quantifying thermal properties of clothing in a 3-D manner compared with the use of hotplates for material testing. The effects of clothing properties measured on the thermal manikins under steady state (constant manikin surface temperature and constant environmental condition) have usually to be validated by human subject tests. The thermal insulation and evaporative resistance values measured in the constant conditions are also used in modeling to calculate heat balance, predict human thermal physiological responses, and thermal comfort. However, in many real life situations, clothing properties (e.g. moisture transfer), in particular the clothing properties with smart materials, e.g. phase change materials (PCMs), environmental conditions, sweating rate, skin temperatures are neither constant nor uniform. These make mathematical modeling complicated to take into account various transient, non-uniform conditions, and changeable properties of smart clothing which is becoming increasingly popular (Tang and Stylios 2006). Moreover, skin and core temperatures rather than heat loss or storage are commonly used to evaluate thermal comfort, define hypothermia and hyperthermia and evaluate heat strain. Therefore, the direct prediction of thermophysiological responses (skin and core temperatures) based on manikin measurements are valid (Psikuta and Rossi 2009), and could be considered another step forward towards direct evaluation of human-clothing-thermal environment interactions.

In the case of measuring a personal cooling system, current standard specifies the measurement of the average heat removal rate from a sweating heated manikin (ASTM F2371-10). This heat removal rate is not constant for the PCMs.

The objective of this study was to investigate the gap between the measured heat removal rate of smart clothing with PCMs obtained on a thermal manikin in a stable state, and clothing effects on local human skin and on core temperature, to compare the difference of the results obtained from both methods, and to highlight the need for developing intelligent thermoregulatory manikins.

METHODS

PCM cooling vest
The cooling vest is made of polyester with separate pockets containing 21 PCM packs. The main ingredients of the PCM are salt mixtures including sodium sulphate and water, and additives (Gao et al. 2010). In this study, the melting temperature of the PCM tested was 21°C. Before and after the tests, the vests were kept at 15 °C overnight for solidifying and preparing for re-use. The total weight of vest 21 was 2 224 (g). The weight of the PCM was 1785 (g). Other clothing worn on the manikin under the cooling vest was only a T-shirt and shorts.

Thermal manikin and measurement protocol
The thermal manikin, Tore, with 17 individually controlled (heating and measuring) zones was used to assess the cooling effect of the PCM vest. Constant surface temperature (34 °C) and constant power (20 W/m^2) modes were used respectively. The constant surface temperature mode followed the same protocol as described in the study by Gao et al. (2010). Constant power mode was used so that it may better reflect the situation when humans have constant metabolic rate. The climatic chamber air temperature (T_a) was kept at 34 °C. For the constant manikin surface temperature mode, it was an isothermal condition, so that there was theoretically no heat loss from the manikin to the environment. Manikin heat losses caused by the PCM, manikin surface temperature, ambient temperature were recorded at 10-second intervals. As the cooling vest covered only the torso of the manikin, the chest, abdomen, upper and lower back zones were included in calculations for determining the cooling effect on the torso. Each condition was tested twice. Average values were used for calculations.

Human subject test
As a pilot study, two male subjects participated in the subject test. Their average age was 45 years, height 1.73 m, weight 78.1 kg. During preparation, all clothes, equipment, and subjects were weighed separately. The rectal temperature (T_{rec}) sensor (YSI-401) was inserted by the subjects at a depth of 10 cm inside the anal sphincter. Skin temperature (T_{sk}) sensors (thermistors ACC-001) were taped on the forehead and left side of the upper arm, forearm, hand, chest, scapula, abdomen, lower back, thigh and calf. After preparation and weighing, the subject entered the climatic chamber (T_a=34 °C, *RH*=30%, and v_a=0.4 m/s) and sat in a workstation and worked with a laptop to simulate ordinary office work. The subjects wore only a T-shirt and shorts during the first hour, and then put on the PCM cooling vest, which was conditioned overnight at 15 °C, and continued working for 1.5 hours. T_{rec} and T_{sk} were recorded by a Labview program (National Instruments, USA) at 15-second intervals. Subjects rated their whole body thermal sensation, wetness sensation on skin and comfort sensation, which was recorded at the beginning and every 10 minutes thereafter throughout the test. Oxygen uptake (VO2) was measured for five minutes between the 5th to 10th minute with MetaMax® I (CORTEX Biophysik GmbH, Germany). Mean torso skin temperature of the subjects was calculated according to the formula, T_{torso}= ¼(T_{chest} + $T_{scapula}$ + $T_{abdomen}$ + $T_{lower\,back}$). Mean torso temperature on the manikin was area weighted.

RESULTS

Cooling effect when a constant manikin surface temperature was used
When the control mode of the constant manikin surface temperature (34 °C) was used, the average torso heat loss is in Figure 1.
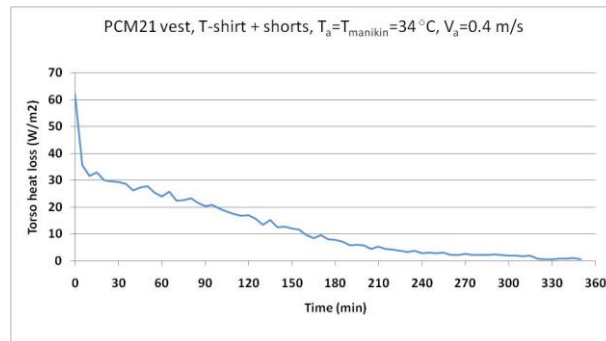

Figure 1. Average torso heat loss on the manikin in the isothermal condition when wearing a T-shirt, shorts, and PCM 21 cooling vest was conditioned overnight at 15 °C

Cooling effect when constant heating power was used
When the control mode of the constant manikin heating power (20 W/m^2) was used, the average torso temperature change is in Figure 2.
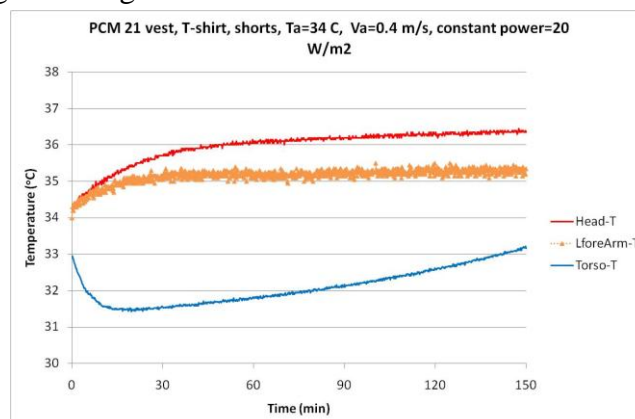

Figure 2. The Torso temperature change on the manikin when wearing PCM 21 cooling vest conditioned overnight at 15 °C, a T-shirt, shorts, T_a=34 °C, manikin heating power at 20 W/m^2

The cooling effects on human subjects
The cooling effects on Torso and core temperature of human subjects in the climatic chamber (T_a=34 °C, RH=30%, v_a=0.4 m/s) are in Figure 3. The average metabolic rate when sitting and working with a laptop was 56.0 W/m^2.
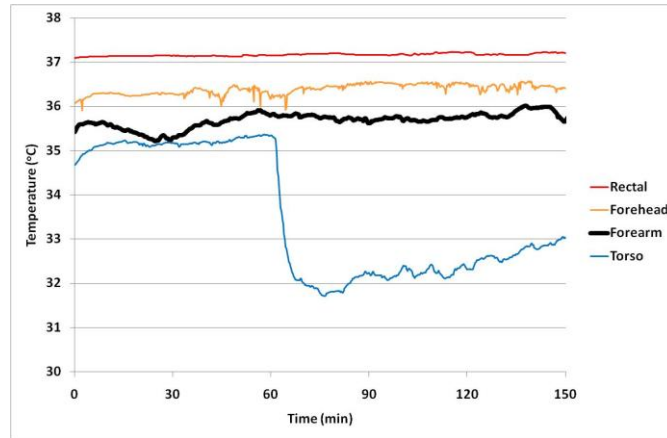
Figure 3. The cooling effects of the PCM 21 vest on human subjects. The subjects wore T-shirt, shorts, sitting and working with a laptop. After one hour, the cooling vest was worn on top of the T-shirt. The cooling vest was conditioned overnight at 15 °C.

DISCUSSION

At present, most thermal manikins are used to determine thermal properties (thermal insulation and evaporative resistance) of clothing (Holmér and Nilsson 1995) rather than thermophysiological effects of the clothing. This paper uses an example to demonstrate the need, possibilities, and benefit to develop such intelligent thermoregulatory manikins. The challenges for engineers, physiologists, modeling scientists are to find appropriate materials and/or thermoregulation models, which correspond to human thermophysiological responses including effects on local skin.

Psikuta and Rossi (2009) used a single-sector cylinder simulator to measure and predict clothing effects on mean skin and core temperature changes. For smart clothing, the prediction of local skin responses is also necessary. As we can see from the example demonstrated above, when the control mode of constant manikin surface temperature was used, the cooling (heat loss) of the PCM is changing over time (see also Gao et al. 2010) and does not correspond directly and intuitively to the thermophysiological responses on the human subjects. The results obtained on the manikin and on the subjects were not directly comparable. On the contrary, when the constant heating power mode was used, the measured temperature change (about 3 °C lower) on the manikin reflects the temperature change on the human subjects. The constant heating power mode corresponds to the case when humans perform the same level of physical activity. The cooling effect on the local skin (torso) temperature was most effective, while other skin area and core temperature maintained unaffected and stable over the measuring period. Of course, the magnitude of the temperature change on the manikin depends on the thermal properties and the mass of the manikin material when there are no in-built sophisticated physiological regulation models. The constant heating power used for manikin was only 20 W/m^2 in this case, whereas the metabolic rate of the human subjects was 56 W/m^2. This difference is caused by the differences of the mass and thermal properties of the manikin material. A simple such type of intelligent

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thermal manikin could possibly be built up using materials which have similar thermal physical properties and mass as a human being. In this sense, manikin Walter (Fan and Chen 2002) could be regarded as such type of manikins when taking into account the fact that about 60% of body weight is water.

Another approach to intelligent thermoregulatory manikins is to integrate physiological regulation models to compensate non-human thermal physical properties of the manikin. Such an approach is being implemented at Measurement Technology Northwest (Burke et al. 2009), and Humanikin (Richards 2010).

CONCLUSIONS

In order to overcome the limitations of current thermal manikins used for directly predicting the thermophysiological effects of intelligent clothing and smart textiles in transient conditions, to minimize human exposures in extreme environments and to reduce the cost and time of tests using human subjects, thermoregulatory manikins with physiological models to measure changeable local skin, mean skin and core temperatures are desirable.

ACKNOWLEDGEMENT

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