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Integrating a human thermoregulatory model with a clothing model to predict core and skin temperatures

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ABSTRACT

This paper aims to integrate a human thermoregulatory model with a clothing model to predict core and skin temperatures. The human thermoregulatory model, consisting of an active system and a passive system, was used to determine the thermoregulation and heat exchanges within the body. The clothing model simulated heat and moisture transfer from the human skin to the environment through the microenvironment and fabric. In this clothing model, the air gap between skin and clothing, as well as clothing properties such as thickness, thermal conductivity, density, porosity, and tortuosity were taken into consideration. The simulated core and mean skin temperatures were compared to the published experimental results of subject tests at three levels of ambient temperatures of 20 °C, 30 °C, and 40 °C. Although lower signal-to-noise-ratio was observed, the developed model demonstrated positive performance at predicting core temperatures with a maximum difference between the simulations and measurements of no more than 0.43 °C. Generally, the current model predicted the mean skin temperatures with reasonable accuracy. It could be applied to predict human physiological responses and assess thermal comfort and heat stress.

1. Introduction

Increasing attention has been paid on human physiological responses, which are widely applied in the thermal comfort and heat stress evaluation, and personal protective clothing design. (Bartkowiak et al., 2017; Dahlan and Gital, 2016; Havenith and Fiala, 2015; Yi et al., 2016). Human physiological responses are regulated through psychological, physiological thermoregulation, and behavioral regulations such as personal (e.g., clothing change), technological (e.g. using an air conditioner), and cultural adjustments (Kurz, 2008). The physiological thermoregulation of human body has a limited capacity, while behavioral regulation is potentially boundless (Schlader et al., 2009). Clothing is required to regulate thermal responses and maintain core temperature in a narrow range when exposed to challenging environments (Neves et al., 2015). Core temperature and skin temperature are two of the most important indicators for human thermoregulation. Therefore, it is necessary to investigate the changes in core and skin temperatures under various environment conditions with different types of clothing.

Several human thermoregulatory models (Fiala et al., 1999, 2001, 2012; Foda et al., 2011; Huizenga et al., 2001; Kim et al., 2013; Lai and Chen, 2016; Lichtenbelt et al., 2004; Nelson et al., 2009; Tanabe et al., 2002; Tang et al., 2016; Zolfaghari and Maerefat, 2010) have been developed and being used in physiological response prediction and thermal comfort assessment. These models are comprised of three parts: a passive system to predict heat transfer between the human body and the environment; an active system to determine thermoregulation through shivering, sweating, vasoconstriction, and vasodilatation; and a clothing model to determine heat and mass transfer through the clothing system. Several of those established thermal models simplified the clothing systems by thermal insulation and evaporative resistance (Wan and Fan, 2008). In fact, the heat and moisture transfer from the skin, through the air gap between the skin and the clothing and the clothing itself to the environment is a complicated process. Therefore, the complicated physical mechanisms of heat and moisture transfer inside clothing materials can hardly be explained clearly by the thermal insulation and evaporation resistance (Li and Li, 2005).

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Nomenclature

B	heat exchange between central blood compartment and each node (W)
C	heat loss through convection from skin (W)
c	heat capacity (Wh/°C)
C_{ch}	shivering control coefficient for core layer of head (W/°C)
C_{dl}	vasodilatation control coefficient for core layer of head (l/h°C)
C_{st}	vasoconstriction control coefficient for core layer of head (l/°C)
C_{sw}	sweating control coefficient for core layer of head (W/°C)
Cld	cold signal (°C)
Clds	weighted skin cold signal (°C)
D	conductive heat exchange rate with neighboring layer (W)
D_L	signals for the vasodilatation
Diff	diffusion coefficient of water vapor (m^2/s)
E	evaporative heat loss from skin (W)
Err	error signal (°C)
ΔH	enthalpy change of vaporization (J/kg)
h	convective heat transfer coefficient (W/m^2K)
J	mass flux (kg/m^2)
K	mass transfer coefficient (m/s)
k	thermal conductivity (W/mK)
p	porosity of fabric
P_{ch}	shivering control coefficient for core layer of head and skin layer of each segment ($W/°C^2$)
P_{dl}	vasodilatation control coefficient for core layer of head and skin layer of each segment ($l/h°C^2$)
P_{st}	vasoconstriction control coefficient for core layer of head and skin layer of each segment (l/C^2)
P_{sw}	sweat control coefficient for core layer of head and skin layer of each segment ($W/°C^2$)
Q	heat production (W)
q	total heat flux (W/m^2)
R	heat loss through radiation from skin (W)
Res	heat loss by respiration at core layer of chest segment (W)
S_{ch}	shivering control coefficient for skin layer of each segment (W/°C)
S_{dl}	vasodilatation control coefficient for skin layer of each segment (l/h°C)
S_{st}	vasoconstriction control coefficient for skin layer of each segment (l/°C)
S_{sw}	sweat control coefficient for skin layer of each segment (W/°C)
S_T	signals for the vasoconstriction
S_w	signals for the sweating
T	temperature (°C)
T_{set}	set-point temperature of each node (°C)
t	time (h)
Wrm	warm signal (°C)
Wrms	weighted skin warm signal (°C)

Greek letter

ε	emissivity
σ	Stefan-Boltzmann constant (W/m^2K^4)
ρ	water vapor concentration (kg/m^3)
τ	tortuosity of fabric

Subscripts

E	environment
F	fabric
FM	inner fabric layer close to the microenvironment
FE	outer fabric layer close to the environment
MC	microenvironment
S	skin

Clothing significantly affects human thermal response because it determines how much heat is exchanged with the environment. Many advanced clothing models (Fan et al., 2000, 2004; Farnworth, 1986; Ghali et al., 2002; Jones, 1994; Li et al., 2013; Zhu et al., 2015) have been developed to simulate the heat and mass transfer in clothing layers considering the processes of diffusion, evaporation, condensation, and sorption. In addition, researches have been investigated on the effects of clothing parameters, such as the pore size distribution, fiber thickness, diameter, and porosity, on heat and moisture transfer in textiles (Li et al., 2002, 2004; Zhu and Li, 2003). In general, these advanced clothing models could simulate the complexity of heat and mass transfer in clothing layers.

To better understand the heat and mass transfer through clothing as well as the thermal responses, several researches combined the thermal models with the clothing models. Lotens (1993) integrated the two-node model developed by Gagge (1971) with a clothing model to predict thermal responses. Based on the clothing models develop by Farnworth (1986) and Jones (1994), dynamic human-clothing-environment models (Hamdan et al., 2016; Salloum et al., 2007; Wan and Fan, 2008; Xu and Werner, 1997) were proposed by integrating the multi-node thermal models with the clothing models to simulate core temperature, skin temperature, and heat transfer. In the above models, the parameters of thermal resistance, evaporative insulation as well as some fabric properties such as density, specific heat, thickness were used to simulate the heat and mass transfer, but the thermal conductivity, porosity, and tortuosity which could also affect the heat and mass transfer were not taken into account. Moreover, none of these models quantitatively evaluated how the air gap affected the human thermal responses. Actually, air gap could significantly change the heat and mass transfer through fabric. However, researches considering the influences of both air gap and fabric properties on human physiological responses are limited, and the relationship between them remains unclear. It is therefore necessary to develop a mathematical model that incorporates the combined effects of air gap and fabric properties to provide a reasonable simulation of overall and local thermal responses.

The aim of this study was to integrate a thermoregulatory model (Yang et al., 2014) with a clothing model based on the work of Min et al. (2007) and Ding et al. (2010) to simulate core and skin temperatures under different environmental conditions taking into account of the human-air gap-fabric-environment parameters. The thermoregulatory model calculated the human thermoregulation and heat transfer within the human body. The clothing model simulated the heat exchange through the microenvironment between the skin and clothing, the heat and mass transfer within clothing, and the heat and mass transfer between clothing and the environment. To examine the prediction accuracy of the developed