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Numerical study on effect of thermal regulation performance of winter uniform on thermal responses of high school student

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ABSTRACT

The objective of the study was to numerically investigate the effect of thermal regulation performance provided by the winter school uniforms varying in wearing methods on thermal responses. A model of human thermal regulation was used to predict the human physiological responses while sedentary in an indoor environment and exercising in an outdoor environment, and further validated against measured data in human trials. TSENS and UCB comfort models were coupled to the thermal regulation model for predicting human thermal sensation. The predictions were then compared with the subjective responses to surveys. The results showed that the thermal regulation model coupled to UCB comfort model presented the potential for providing a means for reasonably accurate prediction of the thermal sensation in both indoor and outdoor environments. Based on the presented model, it was demonstrated that the difference of mean skin temperatures caused by the different wearing methods of school uniforms ranged from 1.26 to 1.99 °C. Thus, the designs on thermal regulation performance provided by the wearing methods of school uniform were extremely important for students to improve their thermal comfort while switching between the indoor and outdoor environments.

1. Introduction

During the process of switching between sedentary activities in an indoor environment and exercising in an outdoor environment, it is hard to sustain human heat balance, especially in winter. The changing environments pose a significant risk to the human body in terms of comfort, performance and health [1–3]. To provide the necessary thermophysiological comfort in the changing environments, clothing ensembles should play the role of a protective barrier between the body and the environment [4]. The proper selection and wearing method of clothing ensembles are of crucial importance for improving the thermophysiological comfort, since different clothing styles and wearing methods affect greatly the clothing thermal insulation [5]. Therefore, the term "thermal regulation performance" in this study is used to define the change of clothing thermal insulation caused by different wearing methods. It is significant to examine the effect of thermal regulation performance of clothing ensembles on the human physiological reaction and thermal comfort under alternatively indoor and outdoor environments.

Since the experimental methodology is costly and time-consuming for determining the physiological reaction and thermal comfort, the numerical simulation method as both a quick and efficient alternative has been widely used in recent years, such as human thermoregulation model and thermal sensation model [6,7]. As Stowijk proposed 25-node human thermal regulation model in 1971, Gagge's 2-node model, Tanabe's 65-node model, 15-segment Fiala model, UCB model with changeable segments appeared gradually in the last decades [8–13]. These thermal regulation models are composed of an active system and a passive system. The active system can regulate the body temperatures in an extreme environment by receiving the signals by the central nervous system (CNS) from the peripheral nervous system (PNS) and reacting promptly, such as vasoconstriction, vasodilatation, shivering and sweating [11]. The passive system simulates the heat transfer within body tissue layers, and between human body and the heat exposure environment [14]. These models have been validated under steady-state conditions and to some extend transient conditions, and applied for the prediction of thermal and perceptual responses, as well as the clothing design [15–18]. Despite all this development, there yet has no international standard or guideline to report these models as a possible evaluation approach, for predicting local and whole thermal sensations in changing environments [19]. The reason might be the lack of a wide range of model validation and application practices [11,15].

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Nomenclature

a	ratio of counter-current heat exchange
B	heat exchange with central blood node, W
BF	blood flow rate, W
C	heat capacity, W h/K
Ch	shivering heat production, W
*C*1	regression coefficient
*C*2	thermal capacities at skin node, W h/K
*C*3	thermal capacities at core node, W h/K
D	thermal conduction, W
E	rate of evaporative heat loss, W
f	clothing area factor
k	thermal conductivity, W/m K
*K*1	factor for effect of whole-body temperature on local thermal sensation
h	heat transfer coefficient, W/m^2 K
LTS	local thermal sensation
p	water vapor pressure, kPa
Q	rate of heat production, W
Qt	rate of sensible heat loss, W
Qb	basal metabolic rate, W
R	thermal resistance, clo
RES	rate of heat loss through respiration, W
s	slope of the linear model
T	temperature, °C
t	time, s
w	skin wettedness
W	heat production due to external work, W
weight	weighting factors
WTS	whole thermal sensation

Greek letters

η	evaporative efficiency (0.85)
ρ	density, kg/m^3

Subscripts

a	air temperature, oC
b	body temperature, oC
b,c	cold set point
b,h	hot set point
cl	clothing
e	evaporative resistance, kPa·m2/W
E	evaporation
CD	conduction, W
CV	convection, W
R	radiation, W
RES	respiration
sk	skin
set	set point

Thermal sensation models has been widely used to evaluate the human's perception in given indoor and outdoor conditions, such as predicted mean vote (PMV), empirical expressions (TSENS) and UCB comfort model [20,21]. The TSENS as one of most common thermal sensation indices was proposed based on Gagge's two-node model [22]. The scale of TSENS is consistence with ASHRAE scale, but with extra terms for ± 5 (intolerably hot/cold) comparing to the scale of UCB comfort model (see Fig. 1). The UCB comfort model based on 9-point numerical scales was developed by a large scale of human trials [23,24]. The model consists of a static term that represents steady state sensation and a dynamic term that is used to evaluate the thermal sensation in transient conditions. The static term is a function of skin temperature from its set point, while the dynamic term is both determined by the time derivative of the skin and core temperatures. The UCB comfort model was validated based on subjective evaluations from human trials in a real vehicle situated in an automobile company equipped with wind tunnel facility that was conditioned to summer and winter conditions. However, the applications of TSENS and UCB comfort models for the changing environments and activity levels need to be further verified by more cases especially when coupled with a thermal regulation model [15].

Thus, the objective of the study is to propose coupled models consisting of thermal regulation and thermal sensation models, thus investigating the effect of thermal regulation performance of winter uniforms on the physiological reaction and thermal sensation in alternatively indoor and outdoor environments. Firstly, a thermal regulation model was used to predict the local skin temperature and the core temperature by inputting environmental, thermo-physiological, and

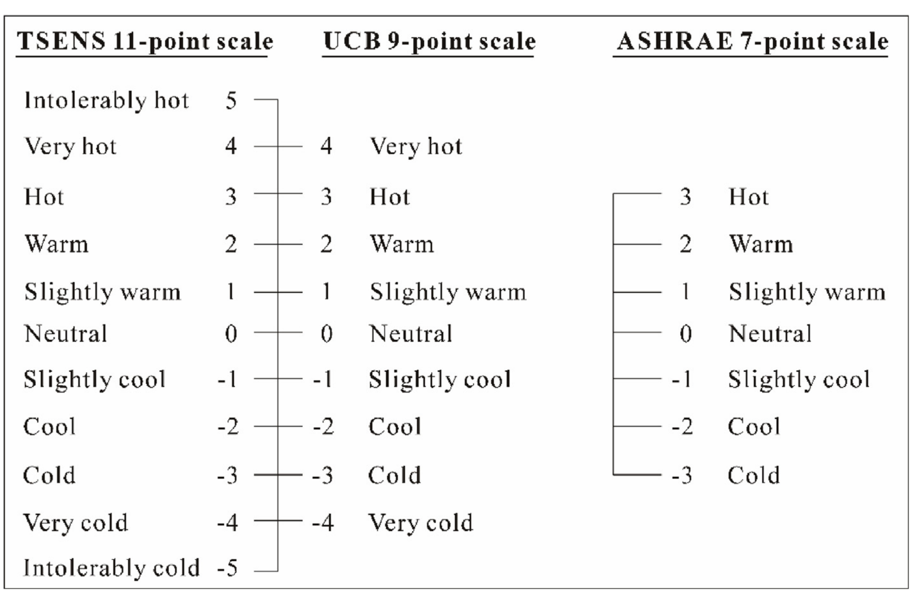

Fig. 1. Thermal sensation scale.