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A method of evaluating the accuracy of human body thermoregulation models

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ABSTRACT

Human Body Thermoregulation Models have been widely used in the field of human physiology or thermal comfort studies. However there are few studies on the evaluation method for these models. This paper summarises the existing evaluation methods and critically analyses the flaws. Based on that, a method for the evaluating the accuracy of the Human Body Thermoregulation models is proposed. The new evaluation method contributes to the development of Human Body Thermoregulation models and validates their accuracy both statistically and empirically. The accuracy of different models can be compared by the new method. Furthermore, the new method is not only suitable for the evaluation of Human Body Thermoregulation Models, but also can be theoretically applied to the evaluation of the accuracy of the population-based models in other research fields.

1. Introduction

The thermal interaction of the human body with the environment involves two processes: i) the heat transfer between the human body and the thermal environment, simultaneously including radiation, convection, conduction, evaporation and respiration; and ii) the self-regulation function of the human body which responds to varied thermal environments, such as vasoconstriction, vasodilation, shivering and sweating [1]. Human Body Thermoregulation Models (HBT models) are developed to simulate these two aspects of interaction and then predict the human thermal physiological responses (e.g. skin temperature, core temperature) under thermal conditions usually with the input parameters of air temperature, radiation temperature, air velocity, relative humidity, clothing insulation, metabolic rate and their variations with exposure time. These models have been widely used in the field of human physiology or thermal comfort studies.

The existing research in this field mainly focuses on developing HBT models using different modelling methods for body segmentation [2–6], thermoregulatory systems [2,7,8], heat transfer [3,5] and numerical solutions [3,9]. It is very important to evaluate the accuracy of the models. However, very little effort has been made to study the methods for evaluating the prediction accuracy of the HBT models. It is still a question under discussion whether the existing model-evaluation methods are generally applicable.

Models predicting the average thermal responses of a group of human bodies are defined as 'population based' model, and this average response is recognized as the 'population mean' in statistics. The existing HBT models are mostly population-based because individual thermal responses vary from one person to another. Two questions in evaluating the prediction accuracy of HBT models are still open: i) How to validate the prediction accuracy of the models in given thermal processes. This is because the users need to have confidence in applying the models in practice. And ii) How to compare the prediction accuracy of models for the same thermal processes. This is to provide guidance for the selection of the most accurate one among different models.

In this paper, the existing evaluation methods for HBT models are summarized and the strengths/weaknesses of these methods are analysed. Thereafter, a new evaluation method for HBT models has been developed.

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Nomenclature

ave_i	mean value of $\mu_{m,i}$ and x_i
CI	confidence interval for population mean
$\overline{d}$	mean difference between sample means and model predictions
d_i	difference between sample mean and model prediction of population 'i'
H0	null hypothesis
HBT	human body thermoregulation
k	number of the populations
LOA	limit of agreement
n_i	number of the samples from population 'i'
N_{ob}	number of the observations
N_{sub}	number of the subjects
RMSE	root mean square error
s_d	standard deviation of the differences between sample means and model predictions
se_i	standard error of sample mean from population 'i'
s_i^2	sample variances from population 'i'
$\overline{T}$	sample mean of skin temperature
T	skin temperature
X_i	population 'i'
$\overline{x_i}$	sample mean from population 'i'
$x_{i,j}$	sample j from population 'i'
α	significance level
μ_a	prediction from Model A
μ_b	prediction from Model B
μ_m	model prediction
μ_i	population mean

Subscript

a	denote of Model A
b	denote of Model B
i	denote of population number
j	denote of sample number
m	denote of model
t	denote of time

2. Existing methods for evaluating the accuracy of HBT models

2.1. Brief literature review

This study has reviewed the accessible research papers published over the last fifty years in regard to the development or improvement of HBT models. In total, twenty-two related papers were selected for the discussion in this paper. The detailed information of model evaluation and evaluation methods in these studies is listed in Table 1. From the table, we can see that among these studies on the HBT models development, four papers proposed models without any evaluation; eighteen papers validated the prediction accuracy of the models and eight papers compared the prediction accuracy of different models.

The methods for evaluating models' accuracy in these papers can be summarized into two categories: i) directly observing the figures by comparing the predicted values from the models with the raw data or descriptive statistics of samples from experiments; which can be termed an 'Observation Method'; and ii) calculating the root mean square error (RMSE) between the model predictions and sample means; hereafter known as the 'RMSE Method'. From Table 1 we can see that fifteen papers utilised the 'Observation Method' and three papers applied the 'RMSE Method' for model validation. Among the eight papers that compared the accuracy of different models; six used the 'Observation Method' and two used the 'RMSE Method'.

Table 1
The methods used to evaluate from existing HBT models papers.

No.	Model reference	Whether the study validated the models' prediction accuracy		Whether the study compared the prediction accuracy of different models	
		Yes (Y) or No (N)	Method used	Yes (Y) or No (N)	Method used
1	[2]	N	N/A	N	N/A
2	[3]	Y	Observation	N	N/A
3	[10]	Y	Observation	N	N/A
4	[11]	Y	Observation	N	N/A
5	[12]	N	N/A	N	N/A
6	[13]	Y	RMSE	N	N/A
7	[14]	N	N/A	N	N/A
8	[15]	Y	Observation	N	N/A
9	[9]	Y	Observation	N	N/A
10	[8]	Y	RMSE	Y	Observation
11	[5]	Y	Observation	N	N/A
12	[4]	N	N/A	N	N/A
13	[16]	Y	Observation	N	N/A
14	[17]	Y	Observation	Y	Observation
15	[18]	Y	Observation	Y	Observation
16	[19]	Y	Observation	Y	Observation
17	[20]	Y	Observation	Y	Observation
18	[21]	Y	Observation	N	N/A
19	[7]	Y	Observation	Y	RMSE
20	[22]	Y	Observation	N	N/A
21	[6]	Y	Observation	Y	Observation
22	[23]	Y	RMSE	Y	RMSE

2.2. Analysis of the existing methods

The 'Observation' and 'RMSE' methods, to some extent, are insufficient to evaluate the prediction accuracy of the HBT models. We use a practical example of real data from our experimental studies for a further explanation (see in Fig. 1).

These black thin lines in Fig. 1 show the raw data of measurements for skin temperatures in a human exposure experiment in which ten half-naked health male subjects experienced a temperature step-change process from The Environment I to the

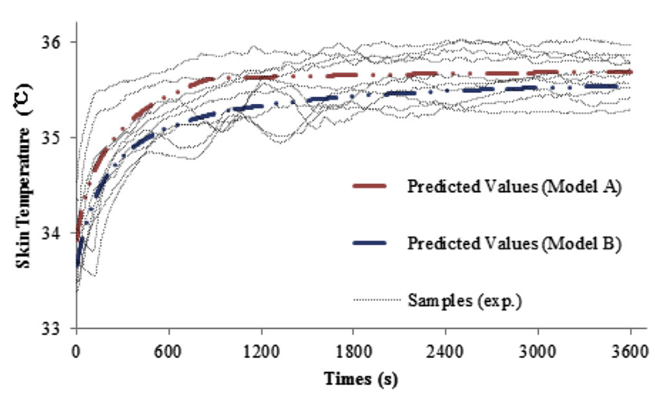

Fig. 1. The raw dataset of predictions and samples.