Thermoregulation Model for the Reference Indian Adult

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Abstract A human thermoregulatory model incorporating morphological details of Indians is established. The study uses the fundamental Stolwijk model with modifications to adapt Indian subject scenario. Good agreement is observed between the model predictions and the experimental data, though small discrepancies are noticed. The study investigated core and skin temperature variation during normal, hot and cold environments of Western and Indian subjects as well as Indian male and female subjects. Effect of BMI, age, clothing and short-wave radiation on thermoregulation is also analysed. The core temperature does not differ significantly in all the cases investigated which indicates that the model is able to capture various human thermoregulatory responses effectively. The most notable difference between Western and Indian subjects is the delay in sweating and lower shivering rates under hot and cold environments, respectively. Indian female subject showed slightly increased mean skin temperature and decreased sweating sensitivity compared to the male counterpart. In a hot environment, female thermoregulatory behaviour is characterised by a lower sweating rate, heat storage and increased mean skin temperature. Comparison between obese and lean Indian male subjects showed no significant difference in core body temperature, while the skin temperature is lower in obese subjects. Deterioration of thermoregulation mechanism with age is incorporated in the model based on available data. The effect of clothing is found to be significant under cold environment. The research establishes the strong link between thermoregulatory response and morphology of humans in adverse environments and highlights the necessity of considering race specificity in human thermoregulatory models.

Nomenclature

A	Age in years
BC	Convection heat exchange between each node and the central blood node (kcal·hr^{-1})
BF	Total effective blood flow (L·hr^{-1})
BFB	Basal effective blood flow (L·hr^{-1})
BMI	Body mass index
BMR	Basal metabolic rate (kcal/day)
C	Heat capacitance (kcal·K^{-1})
c_p	Specific heat (Kcal·kg^{-1}·K^{-1})
CHILL	Output shivering command (Kcal·hr^{-1})
CHILLM	Fraction of total shivering occurring in muscles of segment
COLDS	Integrated output from skin cold receptors (°C)
DILAT	Output skin vasodilation command (L·hr^{-1})
E	Heat losses to the environment through evaporation (kcal·hr^{-1})
H	Height (cm)
HC	Convective heat transfer coefficient for Segment (kcal·cm^{-2}·hr^{-1})
K	Thermal conductivity (W·m^{-1}·K^{-1})
m	Mass per unit surface area (kg·m^{-2})
Q	Metabolic heat generation in each node (kcal·hr^{-1})
PAIR	Vapour pressure in environment (kcal·cm^{-2}·hr^{-1})

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PSKIN	Saturated water vapour pressure at skin temperature (mm Hg)
S	Surface area (m^2)
SKINC	Fraction of vasoconstriction command applicable to skin of segment
SKINR	Fraction of all skin receptors in segment
SKINS	Fraction of sweating command applicable to skin of segment
SKINV	Fraction of vasodilatation command applicable to skin of segment
STRIC	Output skin vasoconstriction command ($L \cdot hr^{-1}$)
SWEAT	output sweat command ($kcal \cdot hr^{-1}$)
t	Thickness (m)
T	Temperature (°C)
TD	Conduction heat exchange between each node and the neighbouring node ($kcal \cdot hr^{-1}$)
TSET	Reference temperature of compartment (°C)
W	body mass (kg)
WORK	Total metabolic rate required for the activity ($kcal \cdot hr^{-1}$)
WARMS	Integrated output from skin warm receptors (°C)
WORKM	Fraction of total work done by muscles in Segment

Greek

ϵ	Emissivity
ρ	Density ($kg \cdot m^{-3}$)

Subscripts

amb	Ambient
b	Blood
cl	Cloth

Introduction

In the past, various analytical thermal regulation models had been developed to simulate thermal response of humans. These models have been used in supporting physiological experiments as well as to analyse human interactions with a variety of environments such as space travel [1], aeroplanes [2], vehicles [3] and buildings [4]. Thermal regulation models developed for predicting the skin temperatures involve passive and active systems of the body [5]. The passive system mainly depends on the individual characteristics of the body such as height, mass, body surface area and fat percentage. Researchers have established that factors like body surface area, body mass, etc. affect heat stress responses of human beings [6, 7]. This requires that at steady states, a smaller person should have higher temperature and vapour pressure gradient between the skin and the environment to achieve the same

effect. In addition, for an equal heat storage rate, a bigger person will take more time to attain stable core temperature under variable thermal conditions [8]. Similar differences in heat stress responses exist between male and female, as the average female is shorter and lighter and thus has a smaller surface area and mass than the male counterpart. The active system controls the body temperature by generating various thermoregulatory commands such as shivering, sweating, vasodilation and vasoconstriction. It is also noted that approximately two-thirds of the resting metabolic rate is spent to maintain the constant body temperature [9]. This heat generation is proportional to the body mass [10] and therefore affects the thermoregulatory mechanism. Wang et al. [11] have studied body mass index (BMI) and percentage body fat of whites and Asians and found that Asians had more upper-body subcutaneous fat. Obesity, the increase in body mass without a proportional increase in height, decreases the surface area-to-mass ratio [12] and results in slower heat loss from the body [13]. Zhang et al. [14] had shown that lean group had higher skin temperature than the normal fat group, though the trend was opposite for the case of rectal temperature. Lichtenbelt et al. [15] showed that by adopting individual characteristics, prediction of skin temperature could be improved. It is observed that there are major differences between Western and eastern people in their body shape and size [16], and therefore, thermoregulatory models have to be tuned to match the population.

Investigation on changes in thermal response due to sex differences is noted during 1960s [17–19]. Uscilko and Ryszard [19] attributed this to the differences in the ratio of body surface area to body mass, subcutaneous fat content and exercise capacity. They also noticed changes in sex hormone release during the menstrual cycle causing modification of thermoregulation in women. Havenith [20] incorporated individualised physical characteristics in thermoregulation model and improved the predictions of heat strain. However, Gagnon and Kenny [21] observed that physiological differences such as skin blood flow, sweat gland activation and output influenced the thermal response. Glickman et al. [22] noticed gender differences in metabolic heat production during cold environmental conditions, though women respond similar to men in their thermal response during both phases of menstrual cycle. Iyocho et al. [23] introduced sex-specific thermoregulation models for analysing thermal response in a variety of environmental conditions. Chaudhari et al. [24] observed significant differences in physiological response due to gender differences and pointed out that it could be beneficial to study each gender group separately. Wang et al. [25] noted that individual differences affect thermal comfort and women were more sensitive to dynamic environmental conditions than men. Kaikaew [26] studied cold

exposure using the Blanketrol®III device and found that men and women responses were different. The role of clothing on the thermal response of the body has been investigated over the past few decades [27, 28]. Gagge et al. [29] considered the role of clothing using constant *clo* value. De Dear et al. [30] noticed variation in the mean skin temperatures due to moisture absorption capability by wool garments. Jones et al. [31] proposed a dynamic model accounting the sorption behaviour of fibres. Li and Holcombe [32] combined Gagge's model and a kinetic sorption model for the clothing to generate a comfort model for humans.

Various human thermoregulatory models are available in the literature to assess the thermal response for a range of environmental conditions. These models incorporated anatomic representation of the body and the physiological responses through a passive and active system approach. One of the simplest models proposed is that of Gagge et al. [29]. He proposed a two-node model with regulatory commands expressed as a function of core and skin temperatures. The basic concepts, algorithms and control aspects of majority of the multi-node models available in the literature were provided by Stolwijk [33]. UC Berkeley [34] developed a comprehensive model with the capability to include unlimited number of segments along with a unique counter-current heat exchange model for blood flow. This model has the capability to predict thermal response under transient and complex radiative environments and is considered to be a milestone in the human thermoregulation model development [35]. The notable extensions from the fundamental Stolwijk's model were Fiala et al. [36], Tanabe and Kobayashi model [37], and Salloum et al. (AUB model)[38]. The AUB model used accurate anatomical data and calculated blood perfusion in the tissue based on the heart rate input. However, this model had the limitation in using in non-uniform environmental conditions [39]. Other examples of multi-node models include Fiala et al. [40], Kingman et al. [41], Novieto [42], Lai and Chen [43], etc. Another category of models developed are multi-element models which simulate human body as various body parts without further dividing it into nodes similar to multi-node models as seen in Ferreira and Yangihara, [44], Sun et al. [45], Tang et al. [46], etc. However, it can be noticed that all the recent and advanced models are improvements and modifications of the fundamental Stolwijk model [33].

In this study, a thermoregulatory model for the Indian people considering the physiological and metabolic characteristics of Indian subjects is established and the thermal responses are investigated for varying environmental conditions. A comparison of thermoregulatory response between Indian and Western adults, Indian male and female subjects, and the effects of BMI, clothing, age and short-wave radiation on thermoregulatory response are also carried out.

Details of the Model Developed

The present analysis is based on the Stolwijk's [33] dynamic model developed for predicting physiological body temperature regulation. The focus of the study is to individualise the model to incorporate Indian adult characteristics rather than modification of the model (number of segments, solution method, etc.), though changes have been carried out to incorporate the effect of clothing. The proposed system consists of two interacting systems—active and passive. The human body, which is the controlled system is also known as the passive system, is modelled by dividing into segments of simple geometries like sphere, cylinders and dividing each segment further into sub-segments such as core, muscle, fat, skin and clothing. Different body segments considered are head, trunk, arms, hands, legs and feet with each segment that consists of various sub-segments or nodes. These nodes will have conduction heat transfer between them, convection heat transfer with blood, and participate in various thermoregulation mechanisms and environmental interaction as shown in Figs. 1 and 2. The passive system senses the external conditions and sends the input signals to the active system. The passive system is defined in terms of its mass, surface area and thermal conductance which are calculated based on the physical characteristics and thermophysical properties.

Various passive system parameters are (i) heat capacitance (C) which is defined as mass times their specific heats, (ii) metabolic heat production (Q). The Q in the muscle node is a summation of the basal heat generated and the work done during shivering (muscles generate heat by rapid contraction and relaxation) when exposed to cold temperatures. As the subject is considered in a resting state, the external work is not considered, (iii) blood flow rate (BF): the blood flow rate of the core and fat is considered same as that of the basal blood flow (BFB). The BFB values for the nodes are taken from the Stolwijk's [33] model. For the muscle node, the blood flow due to the shivering is also considered. The thermoregulatory responses vasodilation and vasoconstriction affect the blood flow in the skin layer largely, and the variation is seen differently in different skin areas. This depends on the skin surface area of the segments, (iv) convection heat transfer (BC) which is the heat transfer through convection between the nodes and the blood, (v) evaporative heat loss (E), the core, muscle and fat layers don't have any evaporative heat loss. The basal evaporative loss is taken as the evaporative loss for the trunk core. Evaporation occurs

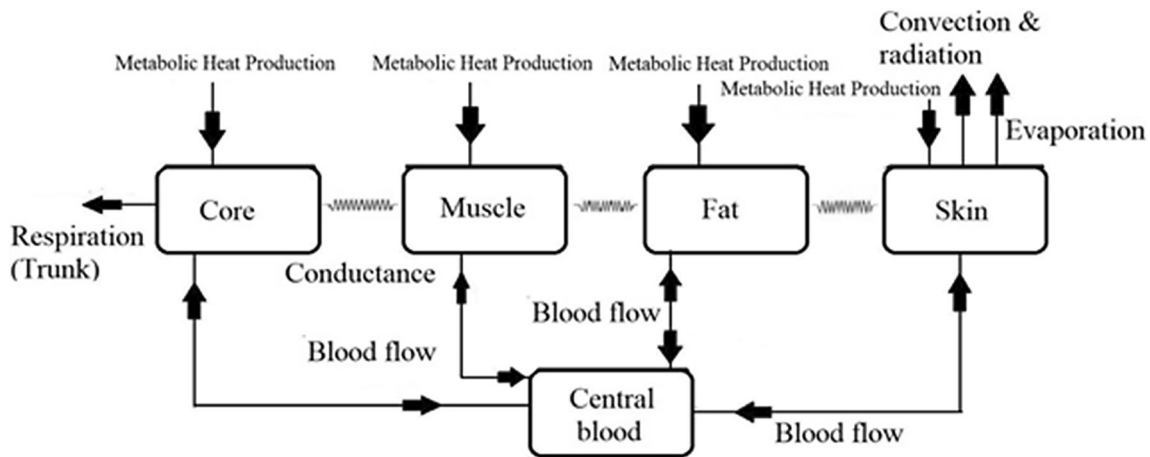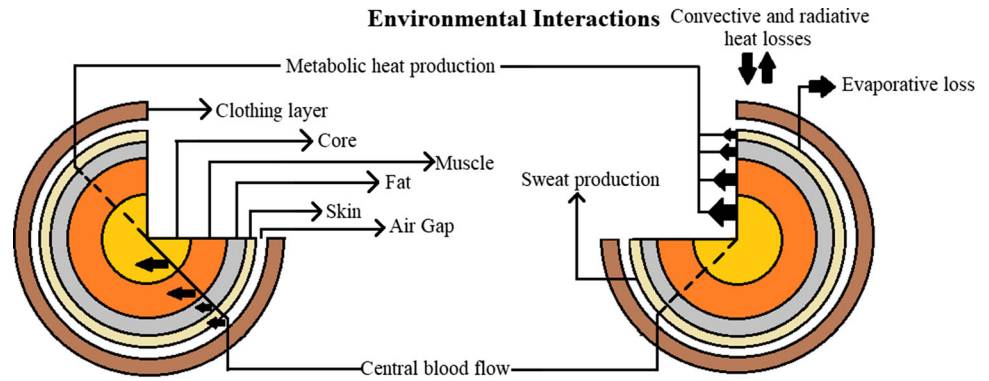**Fig. 1** Details of each segment showing various nodes and its interactions

Fig. 2 Details of each segment showing various heat transfer mechanisms

through the skin layer, and it depends on the sweating command generated which is different for different segment skin layers, (vi) conduction heat transfer (TD) between the nodes and (vii) convection and radiation at the skin surface. The heat balance of nodes of each segment is described as follows:

Core layer : $C_{i,1} \dfrac{\mathrm{d}T_{i,1}}{\mathrm{d}t} = Q_{i,1} - BC_{i,1} - TD_{i,1} - E_{i,1}$

Muscle layer : $C_{i,2} \dfrac{\mathrm{d}T_{i,2}}{\mathrm{d}t} = Q_{i,2} - BC_{i,2} + TD_{i,1} - TD_{i,2}$

Fat layer : $C_{i,3} \dfrac{\mathrm{d}T_{i,3}}{\mathrm{d}t} = Q_{i,3} - BC_{i,3} + TD_{i,2} - TD_{i,3}$

Skin layer : $C_{i,4} \dfrac{\mathrm{d}T_{i,4}}{\mathrm{d}t} = Q_{i,4} - BC_{i,4} + TD_{i,3} - TD_{i,4} - E_{i,4}$

Cloth layer : $C_{i,5} \dfrac{\mathrm{d}T_{i,5}}{\mathrm{d}t} = TD_{i,4} + E_{i,4} - (HC(i)(T_{i,5} - T_{air})$
$$+ \sigma\epsilon\left(T_{i,5}^4 - T_{sur}^4\right)\Big)S(i)$$

$$(1)$$

where i represents body segments; j (1 to 6) represents different layers of core, muscle, fat, skin and cloth layers, respectively. The heat balance of the central blood compartment is given by

Central blood : $C_{\mathrm{b}} \dfrac{\mathrm{d}T_{\mathrm{b}}}{\mathrm{d}t} = \displaystyle\sum_{i=1}^{6}\sum_{j=1}^{5} BC_{i,j}$ $\quad(2)$

The metabolic heat generation for the muscle node is calculated as follows:

$$Q_{i,\mathrm{muscle}} = QB_{i,\mathrm{muscle}} + \mathrm{WORKM}(i)$$
$$\times \mathrm{WORK} + CHILM(i) \times CHILL \quad (3)$$

where WORKM is fraction of total work done by muscles in segment i, WORK is the metabolic rate required, CHILLM is the fraction of total shivering occurring in muscles of segment i and CHILL is the shivering thermoregulatory response generated.

The blood flow in the muscles and skin of segment i is taken as

$$BF_{i,\mathrm{muscle}} = \mathrm{BFB}_{i,\mathrm{muscle}} + Q_{i,\mathrm{muscle}} - QB_{i,\mathrm{muscle}}$$

$$BF_{i,\mathrm{skin}} = \big((\mathrm{BFB}_{i,\mathrm{skin}} + \mathrm{SKINV}(i)$$
$$\times \mathrm{DILAT})/(1 + \mathrm{SKINC}(i)) \times \mathrm{STRIC}))$$
$$\times 2^{\mathrm{ERROR}_{i,\mathrm{skin}}/\mathrm{BULL}} \quad (4)$$

where BULL is the sensitivity parameter; SKINC and SKINV are fraction of vasoconstriction and vasodilation commands applicable to skin of segment i. STRIC and DILAT are the vasoconstriction and vasodilation thermoregulatory responses generated.

The convection between the nodes and blood is calculated as

$$BC_{i,j} = BF_{i,j} \times \rho_{\text{blood}} \times c_{p,\text{blood}} \times \left(T_{i,j} - T_{\text{blood}}\right) \quad (5)$$

The basal evaporative loss is taken as the evaporative loss for the trunk core. Evaporative loss in trunk core is the respiratory water loss and is a function of vapour pressure of the inhaled air. It is calculated as

$$E_{\text{trunk,core}} = (\text{BMR} + \text{WORK}) \times 0.023 \times \left(P_{\text{ex}} - P_{\text{air}}\right) \quad (6)$$

where P_{ex} is the vapour pressure of the exhaled air and P_{air} is ambient vapour pressure.

Evaporation occurs through the skin layer, and it depends on the sweating command generated, skin surface area and number of sweat glands. The expression for the evaporative heat loss for skin is as follows

$$E_{i,\text{skin}} = (EB_{i,\text{skin}} + \text{SKINS}(i) \times \text{SWEAT}) \\ \times 2^{\text{ERROR}(i,\text{skin})/\text{BULL}} \quad (7)$$

where SKINS and SWEAT are fraction of sweating command applicable to skin of segment and thermoregulatory sweating command generated.

Thermal conduction TD between the nodes, convection and radiation at the skin surface, etc. is calculated as

$$TD_{\text{node}} = TC_{\text{node}} \times (T_{\text{node}} - T_{\text{node}+1})$$
$$H_{\text{conv}} = (\text{HC} \times (T_{\text{skin}} - T_{\text{air}}))$$
$$H_{\text{rad}} = \sigma \times \epsilon \times S \times \left(T_{\text{skin}}^4 - T_{\text{air}}^4\right) \quad (8)$$

Body temperature is controlled by a feedback system which requires sensors, controllers and actuators. This is known as the active system. Temperature sensitive receptors present in the body along with hypothalamus act as the sensor unit. Neurons present in the anterior hypothalamic–preoptic region are the controller, warm sensitive neurons create commands to promote heat loss in the event of an increase in body temperature, whereas cold sensitive neurons act to promote heat conservation and metabolic heat generation to increase body temperature. A disturbance in environmental conditions or metabolism resulted a change in the controlled variables of the feedback control system. The feedback along with reference generated the error signal which activates the control centre and corresponding control action. The controller initially calculates the error signal for each of the 25 elements; error (or discrepancy) between temperature, T(node), and set temperature (or neutral temperature), TSET(node), is given by

$$\text{ERROR}(\text{node}) = \text{T}(\text{node}) - \text{TSET}(\text{node}) \\ + \text{RATE}(\text{node}) \times \text{F}(\text{node}) \quad (9)$$

where T is the instantaneous temperature of the compartment; $RATE$ is the dynamic sensitivity of the thermoreceptors. F is the rate of change of temperature. T and F are computed at every iteration from the passive system, whereas $TSET$ and $RATE$ are constants initially provided to the model. The ERROR signal can be positive or negative and based on the sign for each N, positive ERROR is assigned to WARM(node), and the absolute value of the negative signal is assigned to COLD(node). The total receptor outputs WARMS and COLDS for WARM and COLD receptors are obtained by integrating them. The active system generates thermoregulatory commands to regulate the body temperature. The thermoregulatory commands are shivering, sweating, vasodilation and vasoconstriction. The thermoregulatory commands SWEAT, CHILL, STRIC, DILAT for sweating, shivering, vasoconstriction and vasodilation, respectively, are estimated as described as:

$$\text{SWEAT} = 320 \times \text{ERROR}(1) + 29 \times (\text{WARMS} - \text{COLDS})$$
$$\text{DILAT} = 117 \times \text{ERROR}(1) + 7.5 \times (\text{WARMS} - \text{COLDS})$$
$$\text{CHILL} = 21 \times \text{COLD}(1) + \text{COLDS}$$
$$\text{STRIC} = -5 \times \text{ERROR}(1) - 5 \times (\text{WARMS} - \text{COLDS})$$
$$(10)$$

These commands are the result of signals from (i) hypothalamus, ERROR(l), and (ii) the skin (WARMS-COLDS). The generated commands are used for controlling action. Evaporation for the skin will be modified based on the sweat command. Vasoconstriction and vasodilation commands are used for constricting or relaxing of the arterioles near the body's surface to control heat transfer out of the body. This will in turn control the blood flow to the skin layer and the skin temperature. Shivering command will increase metabolic heat generation. These thermoregulatory functions are assigned to various nodes, and heat flows are generated. Change in temperature is estimated by dividing the heat flow by capacitance, and this is iterated using a small integration step till the error command is minimised. Initially, a set of initial reference and the initial temperatures of the segments and nodes are assumed along with a given environmental condition. Based on this, the ERROR signal and various control parameters are calculated. The iteration is done to obtain a final temperature closer to the set point temperature. The model is simulated by implementing an algorithm in a

numerical computing environment, MATLAB. Figure 3 shows the flowchart of the program developed. The detailed description of the model and corresponding empirical relations used are available in Stolwijk [33] and Konz et al. [47].

The input data consist of (i) geometrical inputs such as the surface area of the segments, capacitance ($m \times c_p$), (ii) environmental condition inputs such as ambient temperature, humidity, vapour pressure, air velocity, convective & radiative heat transfer coefficients, (iii) physiological inputs such as basal metabolic, evaporative and blood flow rates, etc., and (iv) temperature inputs such as initial temperature and the reference temperature. The major output from the model is the body temperature though other variables such as evaporation rate, sweat rates and sweat/shiver command can also be obtained as output. 1-min time interval is used as the standard iteration interval. The developed model is used to analyse Western and Indian subjects. The main difference compared to the original model is the individualisation of parameters, addition of clothing layer and modification of governing equations of the model. The changes related to individualisation are described in the following section.

Reference Indian Adult Data

Dang et al. [48] generated data for the physiological and metabolic characteristics of Indian subjects from the extensive nationwide surveys conducted by NNMB [49]. The reference adult male and female have heights 164 and 151 cm, and body mass 53 and 45 kg, respectively. All data used for the current model are described in Table 1. The surface area is determined by the modified DuBois equation proposed by by Mehra [50] and is given by

$$\text{For Indians : Surface area} = 113.1 \times H^{0.647} \times W^{0.409}$$

(11)

The other required parameters for modelling are obtained as described below. The surface area distribution for each segment in percentage is based on Stolwijk [33] and Dubois [51]. The distributions are as follows: head—7%, trunk—36%, arms—13.41%, hands—5%, legs—31.76%, and feet—6.86%. The volume is estimated using the surface area distribution and the lengths of the segments. The radius of each layer is found from the corresponding volume. The percentage of core weight is considered as 15% [52], and the weight percentage of skin is 1/16 of the body weight which is 6.25% [53]. The rest accounts for body fat and muscle weights. Capacitance is the mass of the compartment times its specific heat, and the assumed specific heat values are 0.5 gcal/g°C for the skeleton, 0.6 gcal/g°C for fat and 0.9 gcal/g°C for all other tissues including blood. The thermal conductance between the layers of the segments is calculated by using the already derived method outlined by Stolwijk and Hardy [54].

The basal metabolic rate (BMR) is the minimum amount of calories that are required by the body at rest and it depends on body weight, body type, fat composition, blood flow amount, skin colour, etc. This requires that the metabolic rate may be calculated based on Indian subject
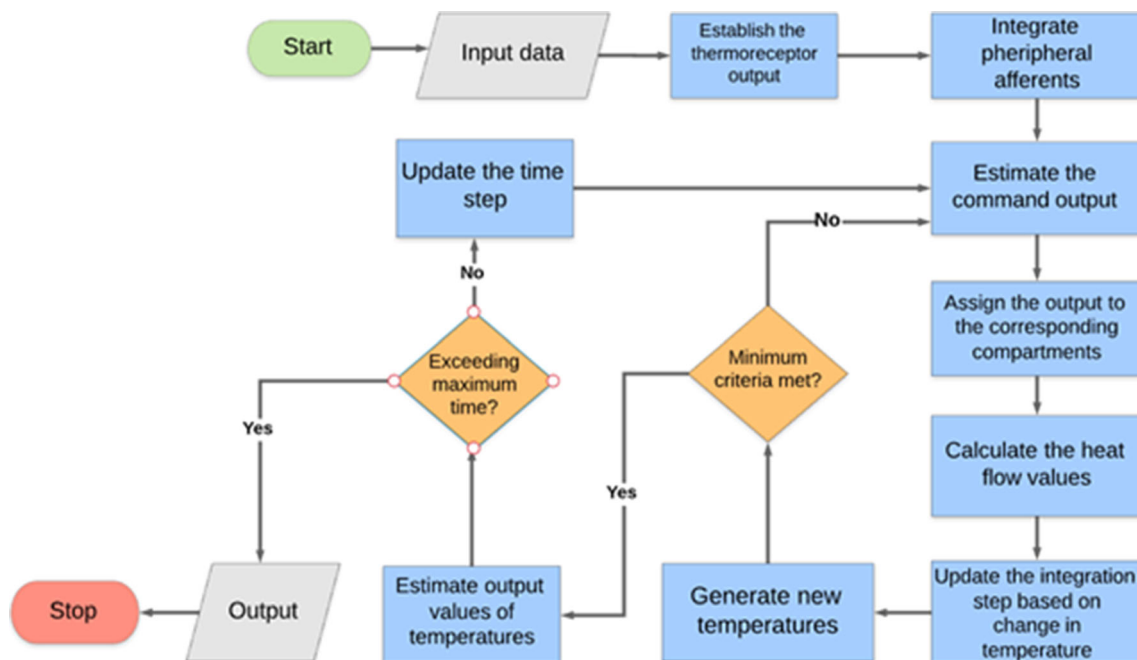

Fig. 3 Flowchart showing the algorithm used in the present model

Table 1 Data for Indian adults

	Male	Female
Height	164 cm	151 cm
Mass	53 kg	45 kg
Head diameter	15 cm	14.5 cm
Blood volume	73.9 ml/kg body wt	
Body fat	6.8 kg	5.5 kg

details. Mifflin et al. [55] proposed a predictive equation for basal metabolic rate based on body weight, height, fat and gender. Amirkalali et al. [56] observed that there was no significant difference between experimental value and the predicted value using this equation. The following equation [56] is used in the present analysis.

$$
\begin{aligned}
&\text{For Males} : \text{Basal metabolic rate}, \text{BMR}(W) \\
&\quad = 10 \times W + 6.25 \times H - 5 \times A + 5 \\
&\text{For Females} : \text{BMR}(W) \\
&\quad = 10 \times W + 6.25 \times H - 5 \times A - 161
\end{aligned}
\tag{12}
$$

where W is the mass in kilogram, H the height in cm and A the age in years. Aschoff and Wever [57] have estimated the metabolic rate of individual segments—brain accounting for 16%, trunk core 56%, skin and musculature 18%, skeleton and connective tissue as 10%. The total evaporative heat loss is considered as 25% of the basal metabolic heat loss [33] and is distributed for each segment skin according to its surface area. Various parameters used in the present study are tabulated in Tables 2 and 3.

The Indian subject geometry is compared with the the Western [33] and Chinese [58] subjects and is shown in Fig. 4. It shows the distribution of surface area over various segments of the body for different models. The difference in the physical parameters such as height, mass, age and sex brings the change in the surface area, body fat percentage, BMR, etc. which will bring differences in the thermoregulatory functioning of the subjects.

Results and Discussions

Validation of the Model

Konz et al. [47] conducted experiments on human subjects in a controlled environment and measured skin and mean body temperature. Figure 5 compares the experimental data and the current model predictions for the head skin, leg skin and overall mean skin temperatures. Current model predictions are reasonably good, with the maximum deviations of around 1 °C for the leg skin temperature. Maiti

[59] conducted experiments by varying indoor temperature from 21 to 33 °C and measured body temperatures of Indian male college students of age 25.18 ± 2.4 years, weight 68.6 ± 8.46 kg and height 1.71 ± 0.05 m. The temperature varied with an interval of 1 °C with a time gap of 10 min. For the validation of the current methodology, an Indian nude subject of height 170 cm and weight 68 kgs in resting state is considered. The predicted and experimental data of mean skin, mean body and mean core temperatures are compared in Fig. 6. The mean deviations from experimental data for the three cases are 1.8, 0.32, and 0.22 °C, respectively. The large deviation observed for the mean skin temperature is due to the clothing effects as the subject was wearing garments with an approximate clothing insulation of 0.47 clo. This difference was noted in the prediction of sweating also as the subject started sweating at an ambient temperature of 30 °C, though the model predicted the sweating only after 33C. It is noted that the mean skin temperatures increased with increase in ambient temperatures until the sweating sets in. The mean body and core temperature predictions are found to be very close to the experimental data. It may also be noted that the sample sizes in the experiments are not large. The current model seems to be reasonably good in predicting mean and core temperature and sweating in a heat stress environment for a nude Indian. The validation of the current model for different subjects and environment proved its ability to predict the human thermal response.

Sensitivity Analysis

A sensitivity analysis is conducted to evaluate and quantify the impact of major passive and active system parameters such as body fat percentage, basal metabolic rate, sweat and shivering commands of the present model. This is done to understand how they contribute to the sustainability of thermoregulation function. Sensitivity analysis is carried out considering Indian male as the reference subject. Subject is exposed to ambient temperature of 25 °C, and the steady core temperature (37.0 °C) is obtained. This state is considered as the reference condition for BMR and body fat sensitivity study. Parameters are then varied from − 50 to 50% keeping all other variables (both passive and active) constant as that of the reference condition. Compared to the reference condition, a lower ambient temperature for a change in parameter means that the body is producing more heat than the normal or the body is rejecting less heat than required. For each BMR/body fat variation, the ambient temperature is varied until the core temperature is same as the reference core. Similar method is adopted for finding the sensitivity associated with shivering and sweating commands. For shivering sensitivity study, $T_{amb} = 20°C$ is considered as the reference

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Table 2 Estimation of thermal conductance between compartments

	Surface Area (in m²)	Volume (in cm³)	Radius (in cm)	Capacitance (in Kcal/°C)
Head				
Core	0.106	692.376	5.48	2.22
Muscle		777.486	5.70	0.24
Fat		862.595	5.90	0.13
Skin		924.702	6.04	0.21
Trunk				
Core	0.546	3214.849	4.23	4.86
Muscle		7134.863	6.30	11.94
Fat		8683.159	6.95	2.58
Skin		8978.803	7.06	1.08
Arms				
Core	0.203	304.674	0.95	0.88
Muscle		763.046	1.50	2.24
Fat		894.981	1.63	0.35
Skin		960.268	1.69	0.38
Hands				
Core	0.0759	72.728	0.50	0.08
Muscle		92.308	0.56	0.05
Fat		134.267	0.68	0.05
Skin		187.414	0.80	0.14
Legs				
Core	0.482	1225.582	1.60	2.64
Muscle		3032.917	2.51	6.78
Fat		3455.042	2.68	0.87
Skin		3667.878	2.76	0.95
Feet				
Core	0.104	115.215	0.55	0.14
Muscle		136.651	0.60	0.05
Fat		195.598	0.72	0.08
Skin		259.905	0.83	0.19

condition, whereas for sweating, it is taken as 35 °C. Figure 7 shows the variation in relative change in T_{amb} with the percentage changes in the parameter. It is noted that BMR and shivering functions have the most significant impact on the thermal response. A decline in BMR and cardiac output is characterised by old people, and this result is an indication of poor thermal response of old.

Comparison of Various Group Under Dynamic Conditions

The performance of the thermoregulatory system is analysed for dynamic conditions by applying impulse input change in environmental conditions. Two different subjects representing different ethnic groups are considered: (i) an Indian subject of height 164 cm and weight 53 kg and (ii) a Western subject of height 1.72 m and weight 74.4 kg. The ambient conditions considered are: air velocity of 0.1m/s and relative humidity of 45%. Analysis is done for three cases: (i) the subject spends 30 min in a neutral environment of 30 °C and the quickly transferred to a hot environment of 45 °C and back to 30 °C with recovery time for 30 min, (ii) the subject spends 30 min in a neutral environment of 30 °C and the quickly transferred to a cold environment of 18 °C and back to 30 °C with recovery time for 30 min, and (iii) the subjects spend 30 min in a neutral environment of 30 °C and the quickly transferred to a cold environment of 18 °C for 30 min, then transferred to a hot environment of 45 °C for 30 min and back to 30 °C with recovery time for 30 min. Various dynamic schemes are represented in Fig. 8. Figure 9 shows the variation in rectal core and skin temperatures for the two subjects in the three

Table 3 Estimation of BMR and evaporative losses

	Thermal Conductance (in Kcal/ °C h)	Basal Metabolic Rate (in Kcal/h)	Basal Evaporative Rate (in Kcal/h)
Head			
Core	0.119	7.46	0
Muscle	6.790	0.18	0
Fat	7.184	0.08	0
Skin		0.04	0.50
Trunk			
Core	0.910	26.15	7.21
Muscle	5.250	4.25	0
Fat	18.743	1.56	0
Skin		0.20	2.59
Arms			
Core	1.429	0.45	0
Muscle	8.180	0.83	0
Fat	30.937	0.21	0
Skin		0.07	0.96
Hands			
Core	1.806	0.05	0
Muscle	12.065	0.01	0
Fat	8.454	0.03	0
Skin		0.02	0.36
Legs			
Core	2.156	1.48	0
Muscle	12.854	2.46	0
Fat	56.268	0.53	0
Skin		0.18	2.28
Feet			
Core	2.284	0.03	0
Muscle	17.154	0.05	0
Fat	11.529	0.01	0
Skin		0.09	0.49

cases. In all the cases, the rectal temperature, i.e. the trunk core temperature, is observed varying in the range of 36.5 °C to 37.5 °C for both subjects. This indicates that the present model is able to predict and control various thermoregulation mechanisms accurately. The higher rise in core temperature of the Western subject compared to Indian is evident in case 1. This shows the efficient adaptability of Indian subject in hot environment. For Indians, sweating is observed at a higher temperature compared to Western people. This is in agreement with the observations of Wijayanto et al. which stated that that the tropical people have a higher cutaneous threshold for sweating. Figure 10 shows the sweating command generated by the present model for the two subjects for case (i). The sweating rate of Western object is almost double compared to Indians under hot conditions.

It is also observed that shivering rate is less for Indian subjects under cold conditions. This might be due to the higher body fat percentage in Asians than whites [11].

Analysis of Thermoregulation in Different BMI Subjects

In this section, the variation in the mean skin, body and core temperatures with various body mass index (BMI) is studied. BMI is calculated as the ratio of a person's mass in kilograms to the height in metres squared. An Indian subject of height 164 cm is considered, and the body mass and other parameters for different BMIs of 15, 20, 25, 30, 35 are estimated. It is noted that the mean skin and mean body temperatures decrease with the increase in body mass index. This is in agreement with the results of Chudecka
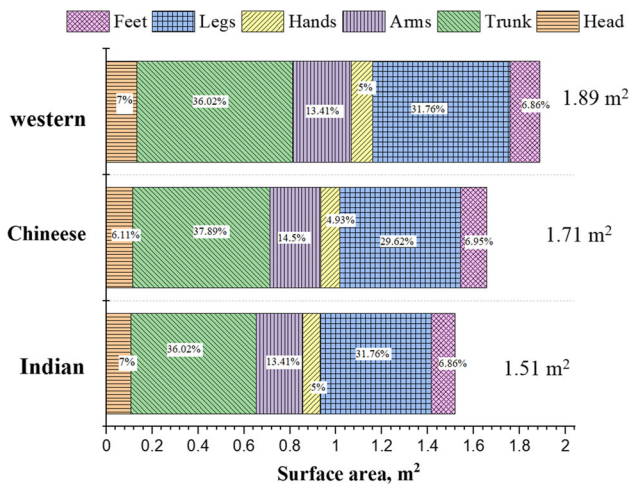
Fig. 4 Distribution of surface area over various segments of the body for different models
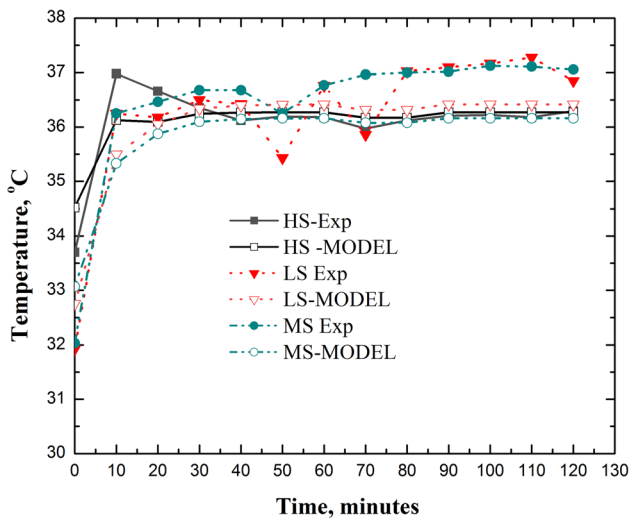

Fig. 5 Comparison of head skin (HS), leg skin (LS), and mean skin (MS) temperatures from the current model and the experimental data of Konz et al. [47]
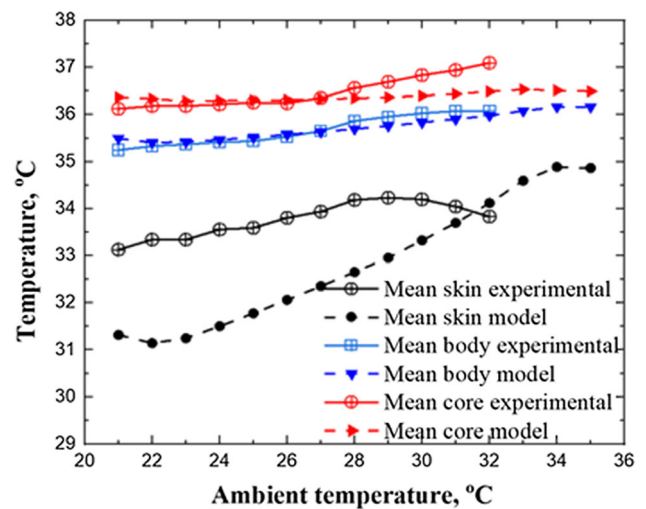

Fig. 6 Comparison of mean skin, mean body and mean core temperatures from the current model and the experimental data of Maiti[59]
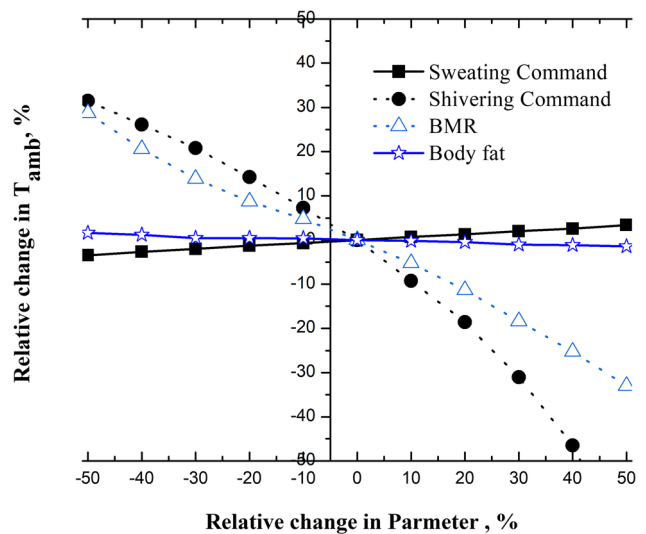

Fig. 7 Sensitivity analysis of various parameters

et al. [60] which studied the thermoregulation in women. The falling in temperature is due to the higher body fat in higher BMI subjects. This increase in fat content acts as an insulation for heat transfer which brings down the sensitivity of the body to respond to external changes in the environment. A comparison of shivering commands showed a higher value of around 30% for lean subjects (BMI=20) compared to obese subjects (BMI=30). It is also observed that no significant difference is seen in core temperatures between subjects of different BMIs and this result agrees with the Hoffmann et al. [61] which says that the core temperature of the body is independent on the composition of the body and remains almost same for a normal, obese and a lean body (Fig. 11).

Effect of Clothing

In order to analyse the clothing effects, a clothing layer is incorporated to the naked subject as an additional layer next to the skin. In the present study, the thermal responses of the naked body are compared with clothing condition for two types of fabrics—cotton and polyester . The parameters of the fabrics considered are shown in table 4 [62]. The simulations are carried out for three ambient conditions: 18 °C (relatively cold), 25 °C (moderate/ neutral) and 40 °C (relatively hot). The mean skin temperature for various cases is shown in Fig. 12. The effect of clothing is significant under cold conditions as it produced approximately 4 °C higher skin temperature compared to the naked body. The difference was only 1.5 °C under hot environment. The
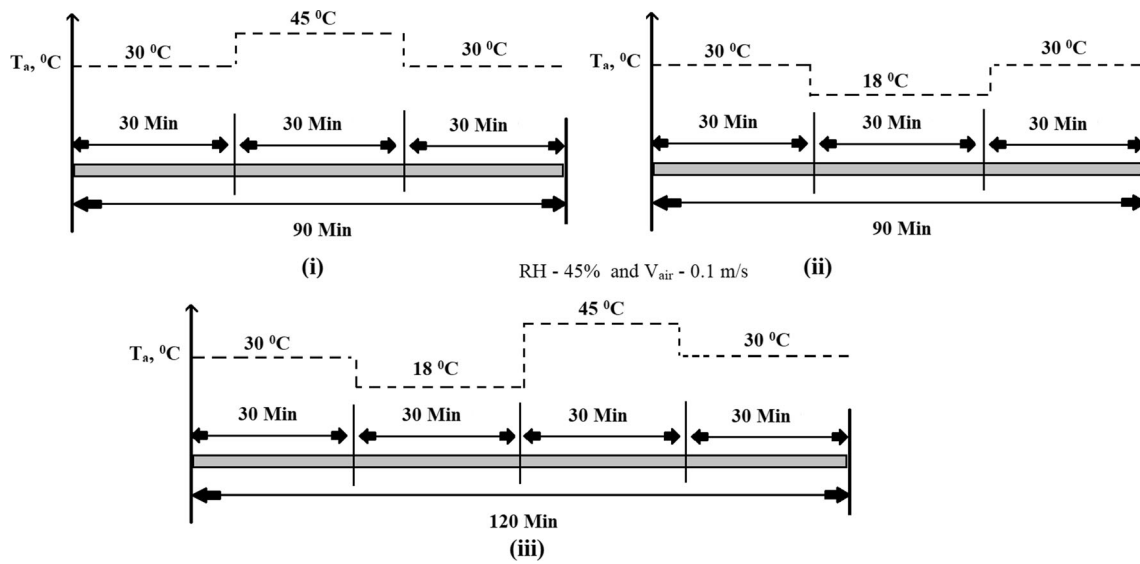
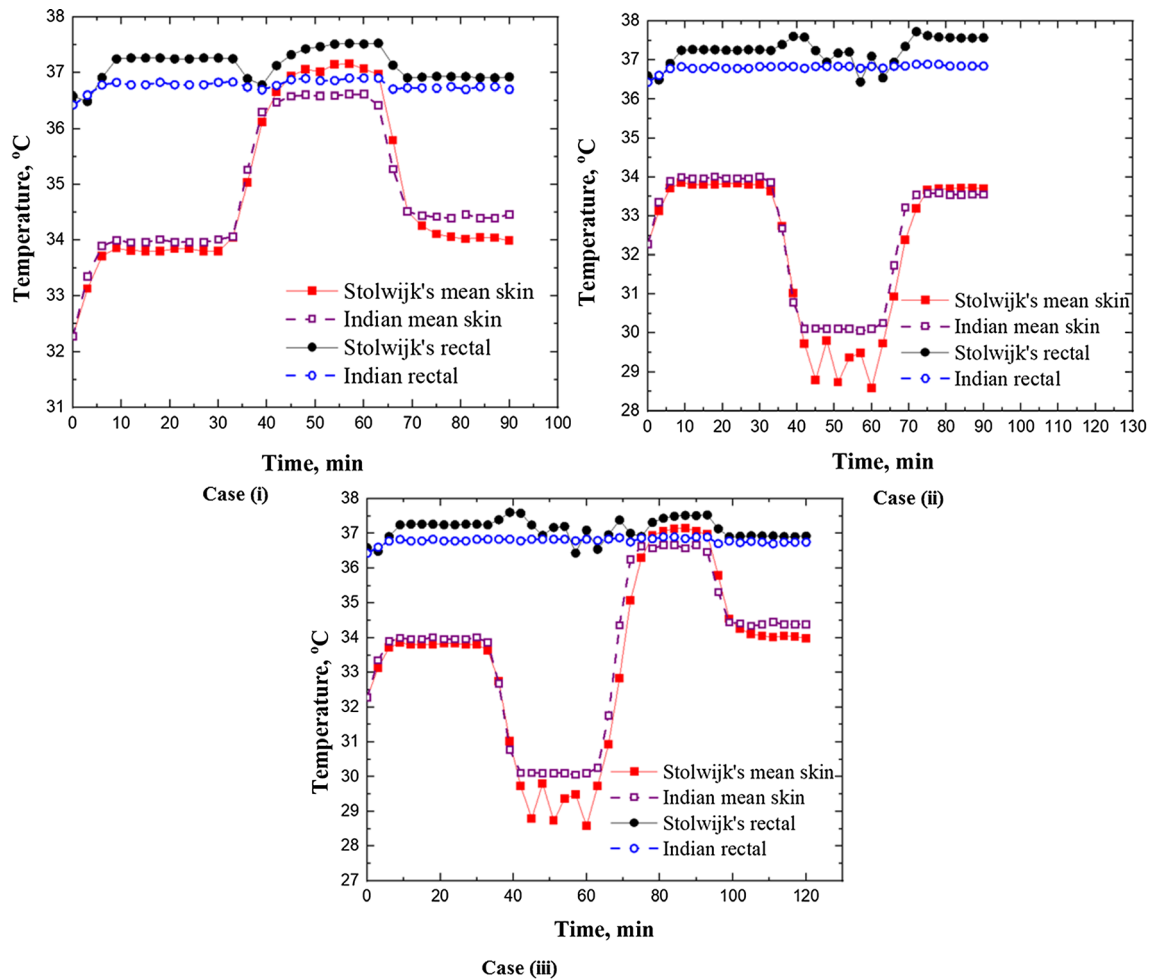**Fig. 8** Various dynamic conditions considered

Fig. 9 Comparison of rectal core and skin temperatures for the two subjects under varying dynamic conditions:(i) Exposure to sudden hot environment, (ii) Exposure to sudden cold environment,(iii) Exposure to sudden cold and subsequently to hot environment
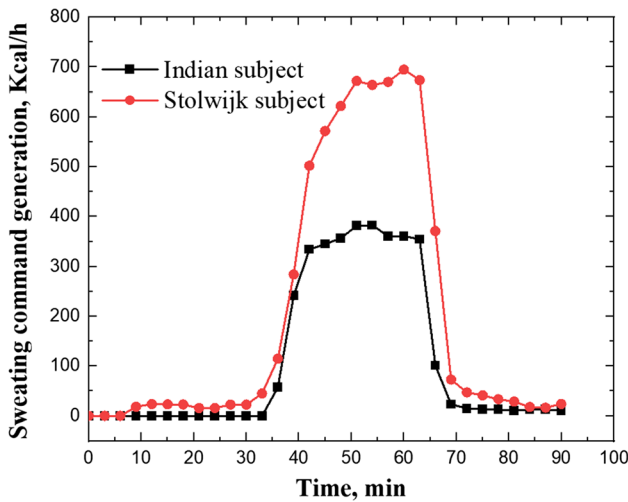
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Fig. 10 Comparison of sweating command generated by the model for the two subjects when exposed to sudden hot environment

Table 4 Physical properties of clothing

Parameter	Cotton	Polyester
m_{cl}	0.1252	0.1272
t	4.9×10^{-4}	4.1×10^{-4}
ρ_{cl}	1550	1390
K	0.23	0.05
C	1210	1340
ϵ	0.77	0.75

shivering rate was found to be lowest with polyester clothing suggesting that it works well in cold weather. Polyester is a non-absorbent material that does not absorb the perspiration off the skin and keeps the body warm when compared to the cotton fabrics. The mean skin temperature of the subject wearing polyester is high under 25 °C ambient and is also experiencing sweating as it is a non-absorbent fabric and restricts the effective evaporation from the skin. Polyester clothing produced highest sweat rate under hot environment of 40 °C. It is also noted that at higher ambient temperatures, the role of the fabric became insignificant.
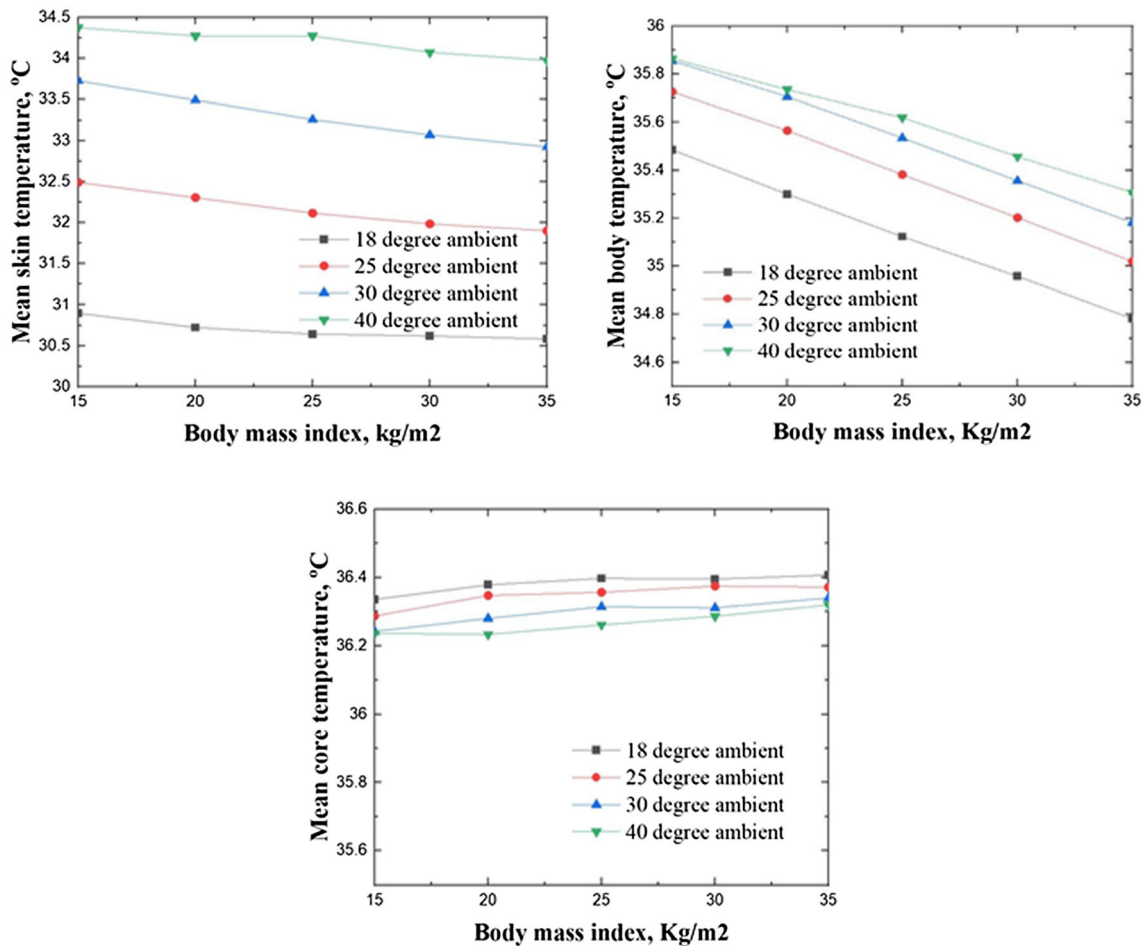

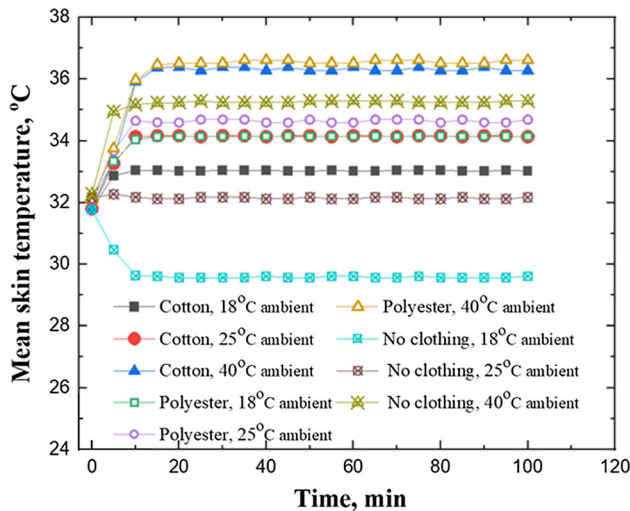Fig. 11 Comparison mean skin, body and core temperatures for Indian subjects with various BMI

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Fig. 12 Comparison of mean skin temperatures for Indian subjects under various clothing conditions

Comparison Between Indian Man and Woman

A comparison of thermal response of Indian male and female subjects is presented in this section. The difference in thermoregulatory mechanism of male and female was noted by many researches [63]. The current model incorporates the differences in physical characteristics as well as physiological gender differences between male and female. Physiological responses are incorporated by carefully selecting sweating and shivering models available in the literature. The variation in the body surface area between the two subjects is found to be around 12%. The values of skeleton mass, body fat, visceral mass and volume of blood are taken from Dang et al. [48]. The skeleton, connective tissue and the viscera are considered under the core
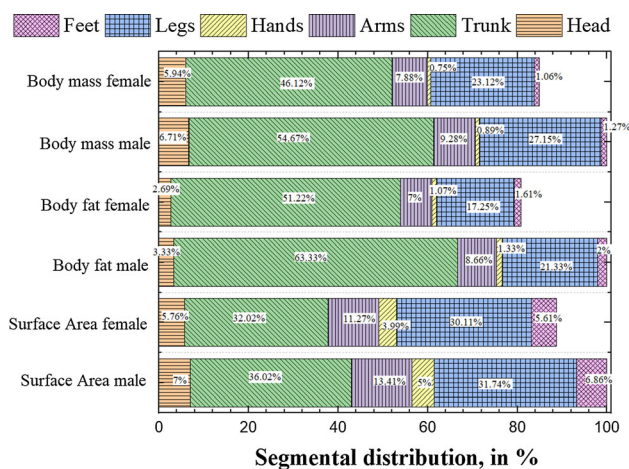

Fig. 13 Segmental surface area, body mass and fat comparison of Indian male and female

segment. The visceral mass is taken as the mass of all the internal organs. The segmental surface area, body mass and fat comparison of male and female are shown in Fig. 13.

A comparison of thermoregulation for the two subjects under conditions: (i) subjects exposed to 30 °C for 30 min, followed by quick transfer to 45 °C, and (ii) subjects exposed to 30 °C for 30 min, followed by quick transfer to 18 °C, is made in Fig. 14. The subject's hot/cold environmental conditions are maintained for 30 minutes after the exposure. Women showed slightly increased mean body temperature and heat storage than man. The higher surface temperature of female along with the tendency of lower BMR than males for a given body mass establishes the difference in fat distribution based on sex. Sweating command comparison between the two objects is analysed for case (i) in Fig. 15a which showed decreased sweating rates for women. It is noted that both subjects respond differently under cold environmental conditions. The woman started shivering at higher environmental temperature, and the generated higher shivering command as shown in Fig. 15b indicates that they are less comfortable under cold conditions. It is observed that the higher body surface area-to-mass ratio of women reduces the capability to maintain the thermal balance under cold conditions and is a major factor determining sex difference.

Comparison Between Young and Old

Anthropometric and thermo-physical properties of older people based on the published research works have been incorporated in the current model to predict the regulatory response. Reduction in skin blood flow response in older men was noted by Pierzga et al. [64] in exposure to heat stress. The study by Dufour and Candas [65] confirmed the reduced sweat output and age. Body mass decrease with age was noted by Ogden et al.,[66], Barllet et al. [67] and an approximate decrease of around 12% is considered in the present analysis. With the increasing age, the fat content increases and muscle decreases as noted by Paolisso et al. [68] Chumlea et al. [69], etc. Based on the evaluation of studies describing the fat increase over the years of the older persons, the current research adopted an increase in fat content by 20%. This produced a muscle decrease of around 11%. Age-related decline in basal metabolic rate is accounted by the Mifflin St Jeor equation and is found to be less by around 12% compared to the young group. A lower core body temperature of around 36.4 °C was noted by Sherwood [70] for old people, and therefore, the current dynamic simulations assumed the initial core temperature accordingly. The average skin temperature at various locations and the core temperature of adult and old are compared in Fig. 16. The older recorded lower temperature of about 0.3 °C at all locations and 0.5 °C in core
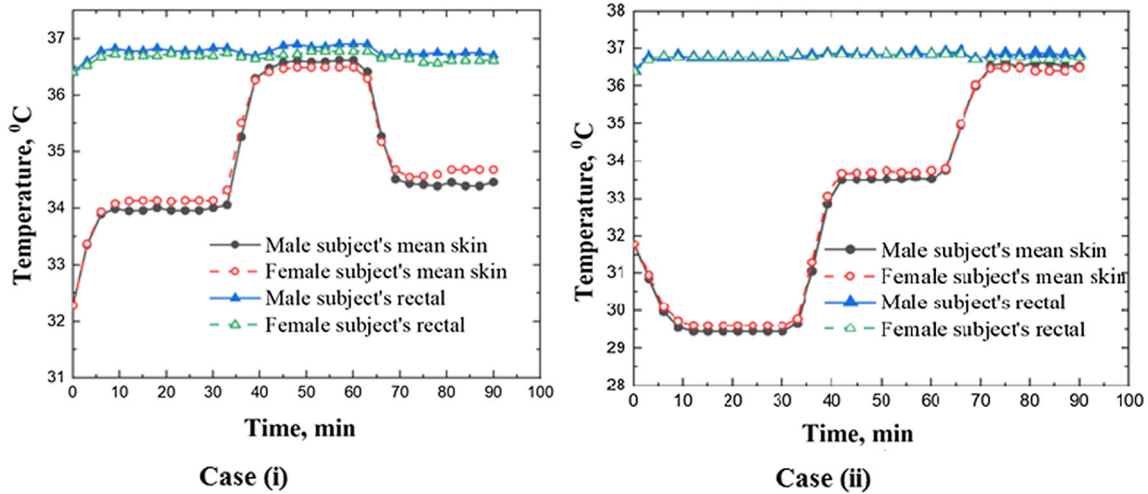
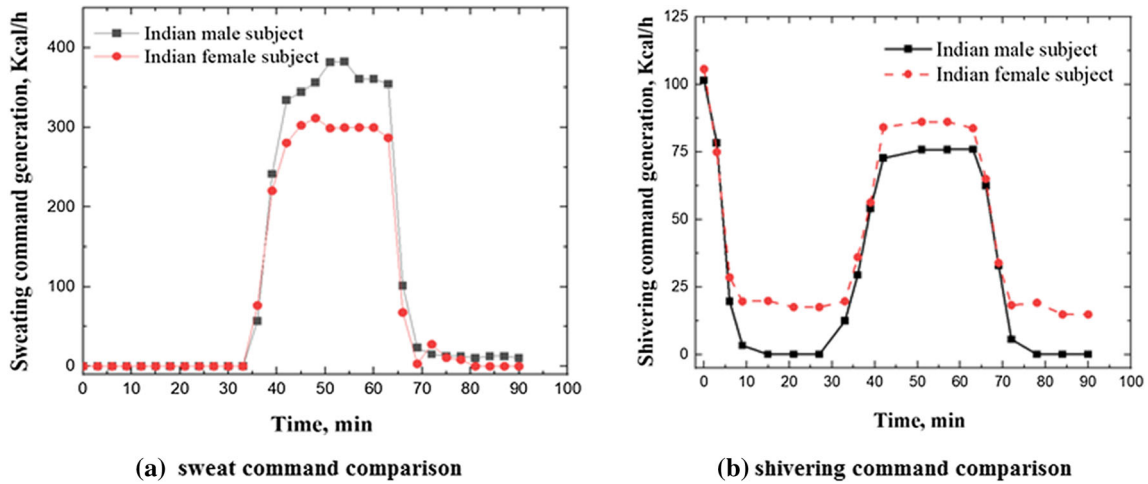**Fig. 14** Comparison of mean skin temperatures for Indian subjects under various clothing conditions

Fig. 15 Comparison of sweating commands for Indian man and woman under hot environmental conditions
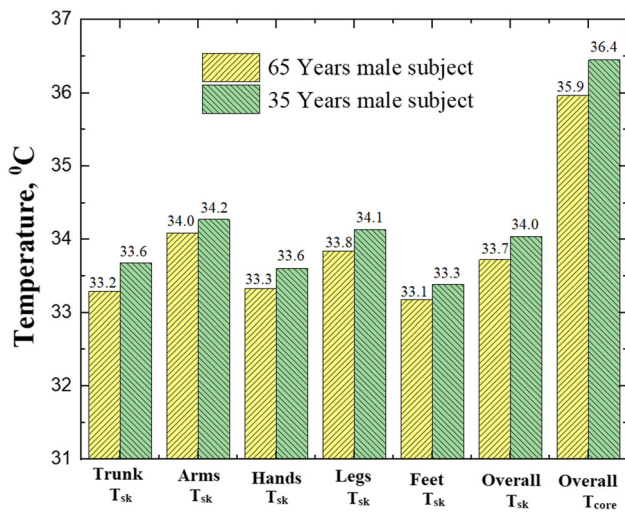

Fig. 16 Comparison under dynamic conditions for old and young

temperature. It can be observed that the feet appear to be the body part with lowest skin temperature among the body segments investigated. The mean skin temperature variation for the dynamic case (case (iii) mentioned in Sect. 4.3) is compared in Fig. 17. In cold environment, the older people could not produce efficient thermal regulation as compared to young people and produced lower skin temperature. Similarly in hot environment, heat loss mechanism is not efficient as young and a delay in command generation, though they reach lower skin temperature. This is because of the initial lower core body temperature of the old.

Effect of Solar Radiation

The effect of surrounding radiation is analysed in this section. This condition may be produced by the solar radiation or hot cabins such as a vehicle. These radiation affects the human thermal response, mean skin temperature
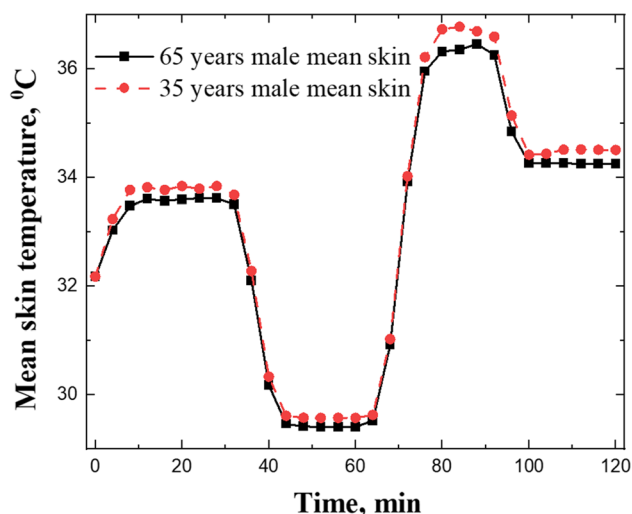
Fig. 17 Comparison of skin temperature of various segments and mean core between young and old people

and the thermal comfort experience. Various uniform radiative heat fluxes ranging from 0 to 600 Wm^{-2} are implemented in the present model along with constant short-wave absorptivity of the body surface. Hodder and Parsons [71] observed that an increase of 2 °C of mean skin temperature for every 200 Wm^{-2} increase in radiation flux. However, it was not clearly mentioned about the location and placement of radiation source with respect to the body. In the present analysis, a uniform radiation source is applied and the variation in mean skin temperature for steady-state conditions is obtained. A linear relation between mean skin temperature and radiation flux is noted with increase of 2.6 °C of mean skin temperature for every 200 Wm^{-2}. A change in absorptivity value of 10% showed a change of around 0.7 °C in skin temperature. The results show that the effects of solar radiation and skin absorptivity play a role in thermal comfort and need to be addressed in thermoregulation models created for various ethnic groups.

Conclusions

The aim of the current study is to expand a previously developed human thermoregulation model for the analysis of Indian male and female subjects including thermal response in a variety of environmental conditions. The investigation used a multi-segment model based on Stolwijk model incorporating anthropometrical, physical and physiological parameters of average Indian adult. The model is tested with the experimental data on Indian subject. In general, good agreement between the two is noticed, and the differences may have been caused by various approximations such as circular cylinder shapes for

body segments, fat percentages, mass distributions, etc. A sensitive analysis is conducted to evaluate the effect of major parameters associated with the active and passive systems of the model. It is noted that changes in BMR and sweating deterioration are critical for the thermal response. Clothing model is incorporated in the present model by considering the properties of the fabric. The comparison of Western and Indian adults, and Indian male and female subjects showed that the interrelation between morphological components and temperature regulation are related. However, the variations are mainly seen in the skin temperature distributions. Higher adaptability under hot environment is observed for Indian subjects. Lower sweating and shivering commands are also noted under hot and cold environments for the Indians compared to Western subjects. The study showed that women have less effective sweating mechanism than men under hot environmental conditions. Results show the importance of sex differences to thermoregulatory mechanisms, especially at hot and cold environment. Another aim of the study is to draw the differences in thermal response of obese and lean Indian adults. The mean surface temperature decreased with the increase in BMI. Anthropometric and thermo-physical properties of older people are incorporated in the model based on available data in the literature. Deterioration of thermoregulatory responses of the elderly is established in the study which necessitates more attention to them under cold and hot environments. The study also evaluated the effect of uniform short-wave radiation for unclothed subjects. In general, individual differences in thermal response between various groups are clearly established in the study. Considering this along with energy co-benefit, the study emphasises the need of considering this aspect in the design and operation of built environments.

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