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Assessment of overall body thermal sensation based on the thermal response of local cutaneous thermoreceptors

Negin Moallemi Khiavi[a], Mehdi Maerefat[a], Seyed Alireza Zolfaghari[b,*]

[a] - Department of Mechanical Engineering, Tarbiat Modares University, Tehran, Iran
[b] - Department of Mechanical Engineering, University of Birjand, Birjand, Iran

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ABSTRACT

In non-uniform environments, different body parts may experience different ranges of physical/environmental parameters. Therefore, to assess the overall thermal sensation in non-uniform environments, the local temperature/thermal sensation of various body parts should be calculated. The local temperature/thermal sensation based on cutaneous thermoreceptor (TRs) responses has been evaluated using MSTB (Multi-Segmental Thermoregulatory Bioheat) model and LTRESP (Local Thermal Response) index in our recent studies. In the present study, a new combined method was proposed to evaluate the overall thermal sensation considering the effects of local sensations of various body segments. In this new method, the local sensations predicted by LTRESP index were defined as the input data for UCB model to predict the overall thermal sensation. So, there was no need to feed it with experimental data to assess the whole-body thermal sensation. Meanwhile, in this method, the overall thermal sensation was predicted taking into account the cutaneous TRs thermal responses. The results indicated that the new combined method could evaluate the overall thermal sensation with a reasonable accuracy under different environmental conditions. Thus, the new method could be practical for predicting the overall thermal sensation in both uniform and non-uniform thermal environments.

1. Introduction

People are usually exposed to non-uniform and transient environments during their daily activities. In these environments, the thermal conditions of individual body segments may be affected by different physical factors such as air temperature, air velocity, and mean radiant temperature. Meanwhile, even considering a uniform thermal environment, different body parts may have different thermal perceptions. This occurs due to several important factors: the different local physiological response of various body segments, the uneven distribution of clothing insulation, different thermal/physiological properties, and different thermal sensitivities of TRs (Thermoreceptors) in various body tissues. It has been reported that the local thermal sensation of various body parts has different effects on the whole body's sensation under various thermal conditions (Arens et al., 2006a, 2006b). For example, a cold thermal sensation in feet may result in cold overall thermal sensation, although the rest of the body parts have a neutral thermal sensation (Cabanac, 1972). Also, local cooling of some body parts with warm thermal sensation may shift the overall thermal sensation towards the neutral zone (Zhang, 2003).

The standard thermal comfort models, Fanger's one-node model (Fanger, 1970) and Gagge's two-node model (Gagge et al., 1971), have provided indices for assessing the whole-body thermal sensation. However, under non-uniform conditions, these scales could not be used as these indices do not have the ability to assess the local thermal sensation. On the other hand, to evaluate the whole body's thermal sensation in non-uniform environments, the effects of the thermal sensation of individual body segments on the whole-body sensation should be considered. In recent years, some studies have been conducted to evaluate the thermal comfort under transient and non-uniform conditions. Most of these models have been based on the regression analysis of experimental results. In addition, many of these models have been developed for evaluating the thermal comfort in vehicles (Ingersoll et al., 1992; Matsunaga et al., 1993, Kohri and Moschida, 2002). In these models, a two-node or one-node model is applied to predict the physiological response and local thermal sensation of various body parts. Applying Fanger (1970) or Gagge (Gagge et al., 1971) models to individual body parts does not address the heat exchange between the body segments induced by blood flow. Hagino and Junichiro (1992) performed a series of tests inside the car to determine the relationship between the overall and local thermal sensations. They captured the overall thermal sensation based on local sensations of

* Corresponding author. P.O.B. 97175-376, Birjand, Iran.
E-mail address: zolfaghari@birjand.ac.ir (S.A. Zolfaghari).

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some body parts which are exposed to air movement or solar radiation in vehicles. So, it is only appropriate for thermal conditions in vehicles.

In recent years, Zolfaghari and Maerefat (2010, 2011) have provided an index for assessing the overall body's sensation under uniform conditions based on the thermal response of skin receptors. This model is not qualified enough for non-uniform conditions due to its limitation on assessing the local sensations. Further, other adaptive thermal models have been developed based on heating/cooling loads of different body segments to provide indicators for assessing the overall thermal sensation in non-uniform conditions (Jin et al., 2012; Fang et al., 2018). He et al. (2016) also provided an adaptive model to evaluate the relationship between local and overall thermal sensations in an air-conditioned dormitory with warm and humid climates. Zhang (2003) as well as Zhang et al. (2010) proposed the UCB model for evaluating the overall body thermal sensation by conducting a series of experiments in a controlled climate chamber. Their experiments were performed in a wide range of conditions including non-uniform, uniform, steady state, and transient thermal conditions. In the UCB model (Zhang, 2003), the overall body sensation was modeled by weighting the local sensations of various body segments. Indeed, a series of weighting factors were defined using regression analysis for individual body parts to assess the overall thermal sensation (Zhang, 2003). The new UCB model (Zhang et al., 2009) applied a new approach to predict the whole body's thermal sensation involving different computational procedures for several thermal conditions. The new UCB model (Zhang et al., 2009) utilized two different models including 'no-opposite sensation' and 'opposite sensation' models, depending on whether any part of body experiences a thermal sensation which is significantly different from the sensations of other body segments. According to a research by Foda et al. (2011), the UCB thermal sensation model (Zhang et al., 2009) had a good accuracy for assessing the overall thermal sensation under various thermal conditions. Therefore, this model is a good option for assessing the whole body's thermal sensation. Nevertheless, to apply this model, the thermal sensation of various body parts should be carefully assessed.

In general, the main goal of this study is to assess the overall thermal sensation based on the thermal response of the skin TRs. But, in order to evaluate the thermal response of TRs, it is necessary to calculate the transient temperature of cold/warm receptors (Ring and De Dear, 1991). So, the temperature of cold/warm TRs was predicted using the MSTB[1] (Moallemi Khiavi et al., 2018a) model, which is the multi-segmental thermoregulatory bioheat model. Afterwards, the local sensations of various body parts must be predicted on the basis of local TRs responses. So, the local thermal sensations were predicted using LTRESP[2] (Moallemi Khiavi et al., 2018b) index, which is the thermal response index on the basis of ASHRAE (2014) scales. Accordingly, in the present study, a new combined method is proposed for assessing the overall thermal sensation. In this new method, the local thermal sensations of various body tissues that obtained through LTRESP (Moallemi Khiavi et al., 2018b) index are defined as input data for the UCB model (Zhang et al., 2009). Therefore, there is no need to feed the new model with experimental data because the local thermal sensation of different body segments could be directly predicted through the LTRESP index (Moallemi Khiavi et al., 2018b).

2. Model description

As mentioned earlier, the main purpose of this study is to introduce a new method to evaluate the overall thermal sensation using the local thermal sensations of various body segments. For this purpose, at first, the temperatures of cold/warm TRs in different body parts are evaluated using the Multi-Segmental Thermoregulatory Bioheat model (MSTB) (Moallemi Khiavi et al., 2018a). Then, the local thermal sensations of individual body parts are predicted using LTRESP (Moallemi Khiavi et al., 2018b) index based on the thermal response of the local skin TRs. Finally, the whole body's thermal perception is predicted using the combination of LTRESP index (Moallemi Khiavi et al., 2018b) and the new UCB thermal sensation model (Zhang et al., 2009). In the following, the MSTB model, LTRESP index, and UCB model are explained in more detail.

2.1. The multi-segmental thermoregulatory bioheat (MSTB) model

The MSTB model is a multi-segmental thermoregulatory bioheat model which has been developed for predicting local transient temperatures of cutaneous thermoreceptors (TRs) of individual body tissues (Moallemi Khiavi et al., 2018a). According to Ring and De Dear (1991), the response of skin TRs depends on the temperature of TRs and its time change rate at the location of TRs. It should be noted that there are two types of cold and warm TRs that are located at the depth of 0.2 mm and 0.5 mm at the skin dermis layer.

The MSTB model basically consists of two main parts: controlled (passive) and controlling (active) parts. In the controlled part, in order to simulate the heat transfer within the local body tissues, the whole body is divided into 16 segments (arms, chest, head, back, pelvis, hands, thighs, legs, shoulders, and feet) and each segment is subdivided into five layers: epidermis, dermis, fat, muscle and core. Meanwhile, the well-known Pennes equation (Pennes, 1948) has been localized and solved for 16 body segments considering appropriate physiological/thermal characteristics for each part. In the active controlling part, a thermoregulatory controlling system has been defined for the MSTB by coupling it with 65-node Tanabe model (65MN model) (Tanabe et al., 2002). The controlling system includes four processes: vasoconstriction, vasodilation, shivering and sweating. Indeed, vasomotion controls the skin blood perfusion, shivering adjusts the metabolic and blood perfusion of muscle layer and sweating controls the evaporation heat loss from the skin. The main differential equation of MSTB model for simulating the heat transfer mechanism within or from the 16 body tissues is as follows:

$$\rho_{ij} C_{ij} \frac{\partial T_i(x,t)}{\partial t} = k_{ij} \frac{\partial^2 T_i(x,t)}{\partial x^2} + \omega_{bl}(i,j)\rho_{bl} C_{bl}(T_{bl}(t) - T_i(x,t)) + Q_{met}(i,j), \quad i = 1{,}16, j = 1{,}5 \tag{1}$$

where, ρ_{ij}(kg/m^3), C_{ij}(J/kgK), and k_{ij}(W/mK)represent the density, specific heat, and heat conductivity, respectively. Also, $T_i(x,t)$ is the temperature distribution of part 'i' including the cold/warm TRs temperatures. Further, $Q_{met}(i,j)$ is the metabolic heat production at each body part and their layers(W/m^3). The letters 'i' and 'j' refer to the body segment and layer numbers, respectively. In addition, $\omega_{bl}(i,j)$(m^3/s.m^3), ρ_{bl}(kg/m^3), C_{bl} (J/kg.K), and $T_{bl}(t)$(°C) are the blood flow rate, density of blood, heat capacity of blood, and blood temperature, respectively. Note that the localized bioheat equation (Eq. (1)) is controlled by the thermoregulatory mechanisms of the 65MN model (Tanabe et al., 2002) at every time step.

Although, the multi-segmental thermal models such as Tanabe model (Tanabe et al., 2002) and Stolwijk and Hardy (1966a, 1966b) model could predict the local skin temperature of various body parts but they could not distinguish the difference between the cold and warm TRs temperature because they consider the skin layer as one lumped node. In fact, they predict one temperature for all nodes of the skin layer. But, the MSTB model is able to predict the local transient temperature of cold/warm TRs at the depth of 0.2/0.5mm under the skin surface of various body parts. Furthermore, in the MSTB model a simple circulatory mechanism was applied to predict the blood temperature. This mechanism simply describes the heat transfer process between each node and the blood source:

[1] Multi Segmental Thermoregulatory Bioheat.

[2] Local Thermal Response.

$$C_{bl}\frac{dT_{bl}}{dt} = \sum_{i=1}^{16}\sum_{j=1}^{4}\rho_{bl}C_{bl}BP(i, j)(T(i, j) - T_{bl}(i, j)) \tag{2}$$

where C_{bl}, ρ_{bl} and BP are the heat capacity, density and the blood perfusion rate, respectively. Also, T (°C) and T_{bl}(°C) are the temperature of each node and blood compartment, respectively.

2.2. The local thermal response (LTRESP) index

The main purpose of the MSTB model was to evaluate the temperature of cold/warm TRs (thermoreceptors) and their rate of variations over time in various body parts to assess the thermal response of cold/warm TRs. After calculating the local time-dependent temperature of TRs, the LTRESP index was applied to evaluate the local thermal sensations of the various body parts based on TRs responses. This index was proposed by Moellemi and Khiavi, (2018b) for assessing local thermal sensation of various body segments based on TRs responses as well as ASHRAE (2014) thermal sensation votes. The frequency thermal response of cold/warm receptors was firstly estimated by Ring and De Dear (1991, 1993) on the basis of Hensel (1981) study:

2.3. Cold receptors

$$R(x, t) = \begin{cases} -\kappa_s(T(x, t) - T_{cR,n}) + b & \partial T/\partial t > 0 \\ -\kappa_s(T(x, t) - T_{cR,n}) + b - \kappa_d\partial T(x, t)/\partial t & \partial T/\partial t < 0 \end{cases}, \quad x = 0.2mm \tag{3}$$

Warm receptors:

$$R(x, t) = \begin{cases} -\kappa_s(T(x, t) - T_{wR,n}) + \kappa_d\partial T(x, t)/\partial t & \partial T/\partial t > 0 \\ -\kappa_s(T(x, t) - T_{wR,n}) & \partial T/\partial t < 0 \end{cases}, \quad x = 0.5mm \tag{4}$$

where $R(x,t)$ is the response of cold/warm receptors (Hz), $T(x, t)$ is the temperature of cold/warm receptors (°C), K_s is the proportionality constant for the static response and K_d is the proportionality constant for the dynamic response. Also, x is the location of TRs under the skin surface. According to Eqs. (3) and (4), the thermal response of skin receptors statically depends on the TRs temperature and dynamically depends on time derivative of TRs temperature. Despite the simplicity and reasonable accuracy of the Ring and De Dear (1991) model, this model has not been applied in thermal comfort studies. Because this model expresses the thermal response of TRs based on Hz, which is not in accordance with the ASHRAE (2014) scales. So, to develop the LTRESP index, Moallemi Khiavi et al., 2018b firstly evaluated the local thermal sensations of different body parts on the basis of ASHRAE scales using UCB local thermal sensation model (Zhang et al., 2010) at several environmental/personal thermal conditions. The UCB local thermal sensation model (Zhang et al., 2010) is represented as follow:

$$sensation_i = 4\left(\frac{2}{1 + e^{-C_1(T_{sk,i}-T_{sk,i,set})-B_1[(T_{sk,i}-T_{sk,i,set})-(T_{sk,mean}-T_{sk,mean,set})]}} - 1\right) + C_{2i}\frac{dT_{sk,i}}{dt} + C_{3i}\frac{dT_{cr}}{dt} \tag{5}$$

where, C_1, B_1, $C_2$and C_3 are the regression coefficients for local thermal sensation model. The subscripts ‘sk’, ‘cr’ and ‘i represent the skin layer, core layer and body segment numbers, respectively. Also the subscript ‘set’ and ‘mean’ describe the set point temperature and the average skin temperature of all body segments, respectively. In addition, T (°C) is the temperature of skin/core layer of individual body tissues. According to UCB local thermal sensation model (Zhang et al., 2010), the local sensation of each body tissue is affected by its local skin temperature. In addition, the local cold/warm TRs temperatures of each part are influenced by its local skin temperature. So, Moallemi Khiavi et al., 2018b considering the formulation represented by Ring and De Dear (1991), described a linear relationship between each body tissue sensation and its TRs temperature using regression analysis:

$$LTRESP_{i,cR} = \min\left\{0.0,\ C_{i,cR}\left(\left(T_i(x_{cR}, t) - T_{in,cR}\right) + \frac{\kappa_{i,d}}{\kappa_{i,s}}\min\left\{0.0,\ \left.\frac{\partial T_i}{\partial t}\right|_{cR}\right\}\right)\right\} \tag{6}$$

$$LTRESP_{i,wR} = \max\left\{0.0,\ C_{i,wR}\left(\left(T_i(x_{wR}, t) - T_{in,wR}\right) + \frac{\kappa_{i,d}}{\kappa_{i,s}}\max\left\{0.0,\ \left.\frac{\partial T_i}{\partial t}\right|_{wR}\right\}\right)\right\} \tag{7}$$

$$LTRESP_i = LTRESP_{i,cR} + LTRESP_{i,wR}\quad, \ i = 1,16 \tag{8}$$

In Eqs. (6)–(8), $LTRESP$ is the thermal response of cutaneous thermoreceptors (TRs). $\kappa_{i,d}$(K^{-1}) and $\kappa_{i,s}$($s^{-1}K^{-1}$) are the proportionality constants for dynamic and static responses, respectively. $C_{i,cR}$(K^{-1}) and $C_{i,wR}$(K^{-1}) denote proportionality constants for cold and warm receptor responses, respectively. T (°C) and x are temperature and location of the cold/warm receptors. The subscripts ‘cR’ and ‘wR’ refer to the cold and warm receptors, respectively. Also, ‘i’ and ‘n’ denote the body segments numbers and neutral condition, respectively. The ratio of proportionality coefficients of local thermal response ($\kappa_{i,d}/\kappa_{i,s}$) is nearly constant and its value is approximately 25 for different thermal conditions (Ring and De Dear, 1991; Ring et al., 1993; Zolfaghari and Maerefat, 2011). According to Eqs. (6) and (7), the LTRESP index includes two main parts: static and dynamic. The static part depends on the receptors’ temperatures while the dynamic part depends on the rate of variations over time for TRs temperatures at the locations of the receptors under the skin surface.

2.4. The UCB overall thermal sensation model

Zhang et al. (2009) provided a novel method for assessing the whole body's thermal sensation under various environmental conditions, consisting of no-opposite sensation and opposite sensation models. In the following, the two mentioned models are discussed in more detail.

2.5. No-opposite sensation model

The no-opposite sensation model is applied in the following situations and conditions:

- Uniform conditions
- Local cooling of a body segment when the rest of the body parts feel cold.
- Local heating of a body segment when the rest of the body parts feel warm.
- Slight feeling of warm/cold in one or more body parts when the rest of the body feels cold/warm.

This model is not applicable when a body part is under significant cooling/warming while the rest of the body parts feel warm/cold. Nevertheless, the no-opposite sensation model is equipped with different methods for the thermal region near the neutral conditions ($|LTS < 2|$) and far from neutral conditions ($|LTS \geq 2|$). However, for conditions far from neutral zone, the overall sensation for both cold and warm sides is determined using a weighted average of the most extreme sensation plus the third-most-extreme sensation. The mentioned formulations for two thermal conditions are as below:

For warm side:

$$OTS = 0.5LTS_{max} + 0.5LTS_{third\ max} \tag{9}$$

For cold side:

$$OTS = 0.38LTS_{min} + 0.62LTS_{third\ min} \tag{10}$$

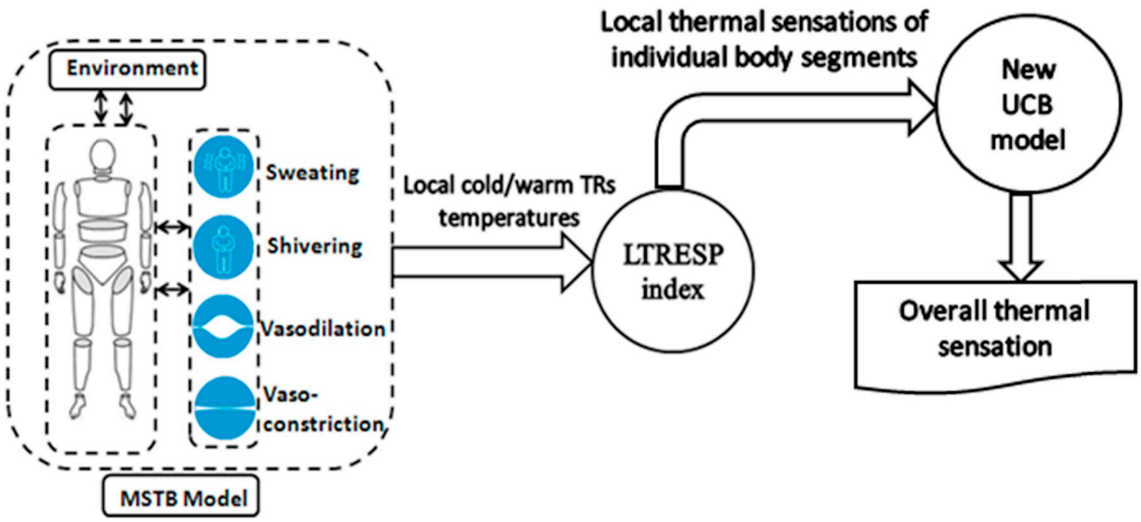

Fig. 1. The conceptual chart of the new combined method.

where, *OTS*[3] and *LTS*[4] are the overall and local thermal sensations.

However, for conditions near neutral zone ($|LTS < 2|$), a gradual method has been used (Zhang et al., 2009). As local thermal sensations are closer to the neutral zone, the most effective local sensations begin to reduce their effect on the overall sensation. Thus, the whole-body thermal sensation is obtained approximately by averaging the local sensation of different body parts. Indeed, the less-extreme sensations are gradually added to the extreme sensations to obtain the overall thermal sensation. This method is called a gradual method.

2.5.1. Opposite sensation model

When a local cooling is applied to one or more body parts, while the rest of the body has a warm sensation or when local heating is applied to one or more body parts while the rest of the body has a cold sensation, these local sensations are considered as the opposite thermal sensations. The opposite thermal sensation must be strong enough to influence the whole body's sensation. The threshold is ± 1. This means that a segment of the body could be considered an opposite sensation if its value is larger than one. In this model, local sensations of different segments are divided into two groups: the larger group, which represents the whole-body thermal sensation, and the smaller group, which represents the opposite thermal sensation. To predict the sensation of the larger group, the no-opposite sensation model is used. The body parts that belong to the smaller group (with opposite thermal sensation) tend to affect the sensation of a larger group. For each of the smaller group members, an individual force is defined as below:

$$Individual_{force} = a(\Delta LTS - c) + b \tag{11}$$

where, ΔLTS is the difference in local thermal sensation of individual segment, ‘a’ shows the slope coefficient representing the ability of individual segment to affect the overall sensation, with ‘b’ and ‘c’ being the regression coefficients.

After calculating the individual forces, a combined force is determined using two individual forces, which is used to modify the larger group's overall sensation:

$$combined_{force} = \max \text{individual}_{force} + 10\%\text{second max individual}_{force} \tag{12}$$

Finally, the combined force is added to the thermal sensation of the larger group to obtain the overall sensation:

[3] Overall Thermal Sensation.
[4] Local Thermal Sensation.

Table 1
The individual and environmental conditions of Cheong et al. (2007) experiments.

case	T_a at 0.6 m(°C)	Δt(K/m)	RH(%)	Clo	V_am/s
1	20	1	50	1.15	0.10
2	20	3	50	1.13	0.07
3	20	5	50	1.12	0.09
4	23	1	50	0.91	0.10
5	23	3	50	0.89	0.07
6	23	5	50	0.89	0.08
7	26	1	50	0.64	0.08
8	26	3	50	0.64	0.07
9	26	5	50	0.63	0.08
10	20	1	50	0.73	0.05
11	20	3	50	0.73	0.01
12	20	5	50	0.77	0.01
13	26	1	50	0.82	0.03
14	26	3	50	0.85	0.02
15	26	5	50	0.80	0.01

$$OTS = TS_{overall,bigger-group} + [combined_{force}] \tag{13}$$

where, TS is the thermal sensation of the larger group.

Accordingly, in the new method, the temperature of the tissue/thermal receptors of various body parts is firstly assessed = using the MSTB model (Moallemi Khiavi et al., 2018a). Then, through the LTRESP index (Moallemi Khiavi et al., 2018b), the local thermal sensations are predicted based on the TRs thermal response. Finally, the local thermal sensation obtained from the LTRESP index is defined as the input data for the UCB thermal sensation model (Zhang et al., 2009), which predicts the whole body's thermal sensation based on opposite sensation or no-opposite sensation models. The conceptual chart of the new method is illustrated in Fig. 1, which depicts the combination of the MSTB model, LTRESP index, and UCB thermal sensation model.

3. Results and discussion

In order to validate the predicted whole-body thermal sensation, the results of the new model were evaluated under various uniform/non-uniform conditions. Firstly, the validation was performed using 15 different cases of Cheong et al.‘s study (2007) with different air temperatures and different vertical temperature gradients. The individual and environmental conditions of Cheong et al. (2007) experimental cases are listed in Table 1.

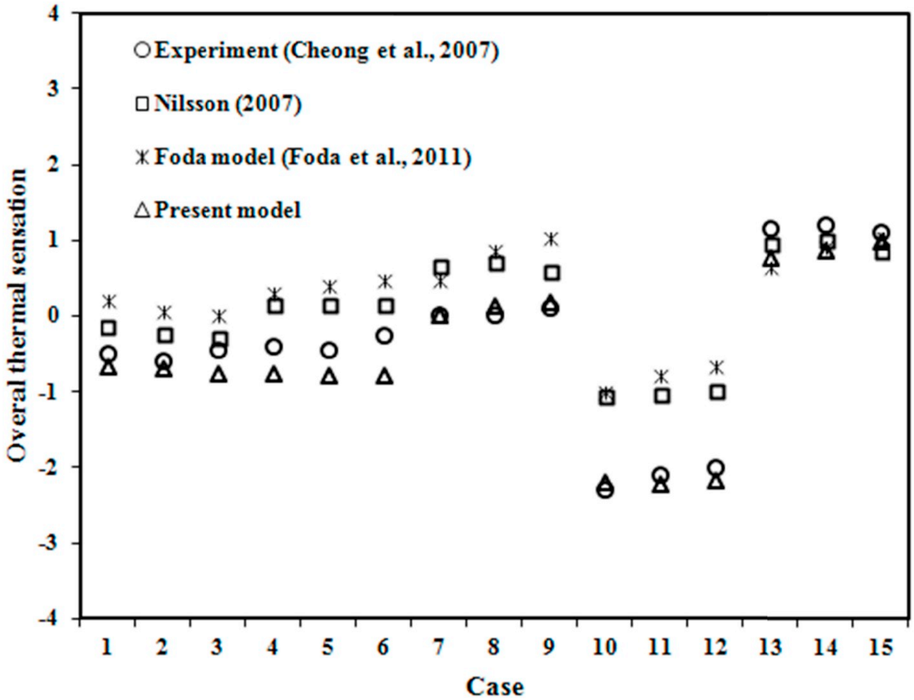

Fig. 2. Comparison of predicted overall thermal sensation and measured data (Cheong et al., 2007).

Table 2
Maximum and average error between the predicted and measured overall thermal sensation for the experiments of Cheong et al. (2007).

Cases	Foda model (Foda et al., 2011)	Nilsson (2007)	Present model
Err_{avg}	0.75	0.55	0.21
Err_{max}	1.34	1.23	0.51

In Fig. 2 and Table 2, the predicted overall thermal sensation using the presented new method, Foda model (Foda et al., 2011), and Nilsson model (2004; 2007) has been compared with Cheong et al.'s findings (2007). Meanwhile, the average and maximum error between the predicted results and experimental data for the 15 cases are presented in Table 2.

As can be observed, the predicted values of overall thermal sensation evaluated by the new combined method for 15 different cases are

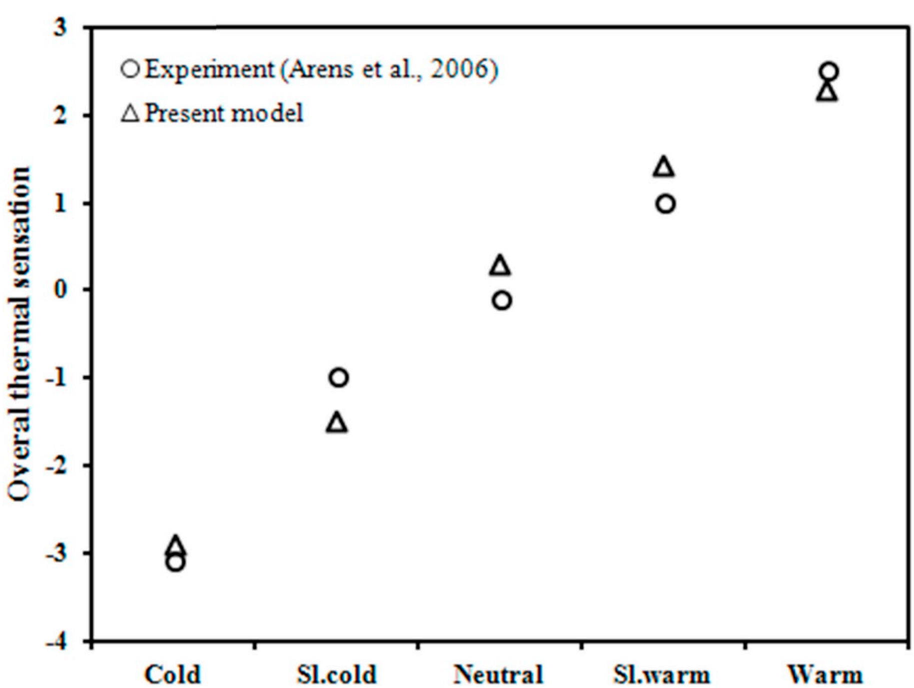

Fig. 3. Comparison of predicted and measured overall thermal sensations.

Table 3
The environmental parameters of Fang et al. (2018) experiments.

Case	T_a (°C)	RH (%)	V_a (m/s)	T_{mrt} (°C)
1	25.9	41.5	0.08	25.5
2	25.9	60	0.11	25.4
3	25	80.6	0.11	25.4
4	27	41.5	0.11	28.7
5	28.1	60.2	0.10	28.5

in good agreement with the experimental data. The mean and maximum errors of the new method for the 15 cases were about 0.21 and 0.51, indicating acceptable performance of the new model under non-uniform conditions.

For validation under uniform conditions, five experiments performed by Zhang (2003; Arens et al., 2006a; Zhang et al., 2009) were considered including uniform, cold, slightly cold, neutral, slightly warm, and warm conditions. In these experiments, the subjects with typical office activity and clothing insulation of 0.32 clo were exposed to five different conditions. Fig. 3 demonstrates the comparison between the results obtained from the present study and the experimental data (Zhang, 2003). As can be seen, the new method could estimate the thermal sensation for the whole body with an average and maximum error of 0.23 and 0.36 respectively, which is reasonable accuracy.

In addition to the experiments of Zhang (2003; Arens et al., 2006a; Zhang et al., 2009), the experimental data of Fang et al. (2018) have also been used for validation. These experiments were conducted in five different cases with different temperatures and relative humidity. The environmental conditions of these experiments are presented in Table 3.

In Fig. 4, the whole-body thermal sensation obtained by the new method has been compared with experimental data of Fang et al. (2018). Also, in Fig. 5, the overall sensation variations over the 90 min period have been compared with the reported data for the “Case 5” of Fang et al. (2018) experiments. Meanwhile, in both of these figures, the results from the TSENS index (Gagge et al., 1971) were compared to the experimental data for the five corresponding tests. According to Figs. 4 and 5, the predicted overall thermal sensation shows a good agreement

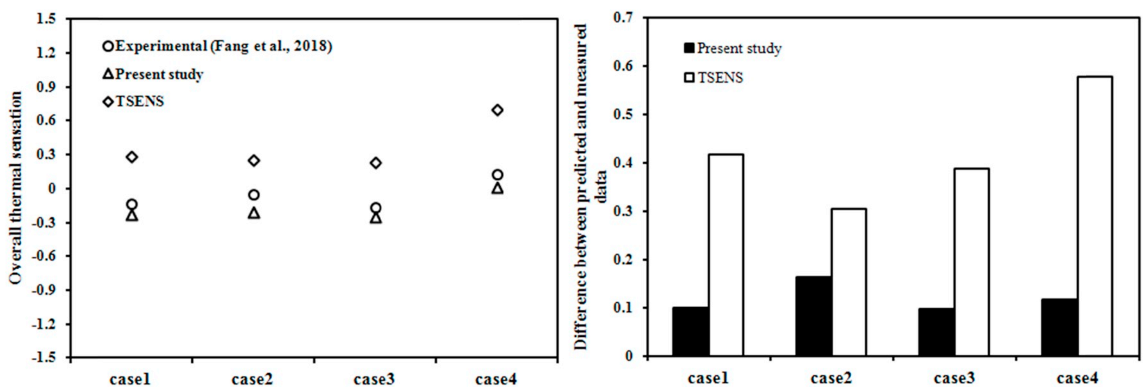

Fig. 4. The comparison of the predicted overall thermal sensations using the present model and TSENS index (Gagge et al., 1971) as well as empirical data (Fang et al., 2018).

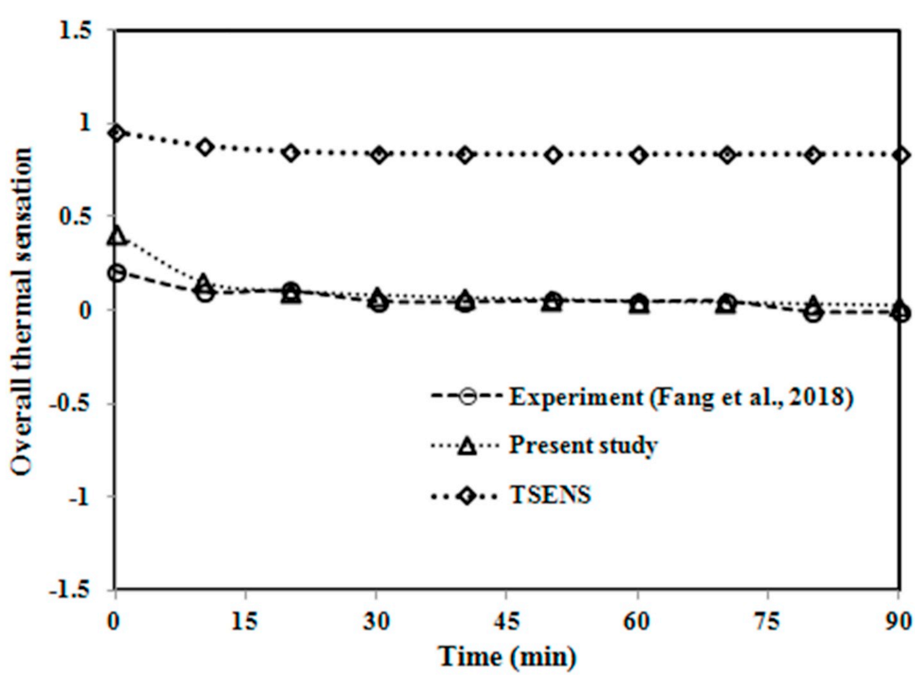

Fig. 5. The comparison of the predicted overall thermal sensations using present model and TSENS index (Gagge et al., 1971) as well as reported data of Fang et al. (2018) experiments (Case 5).

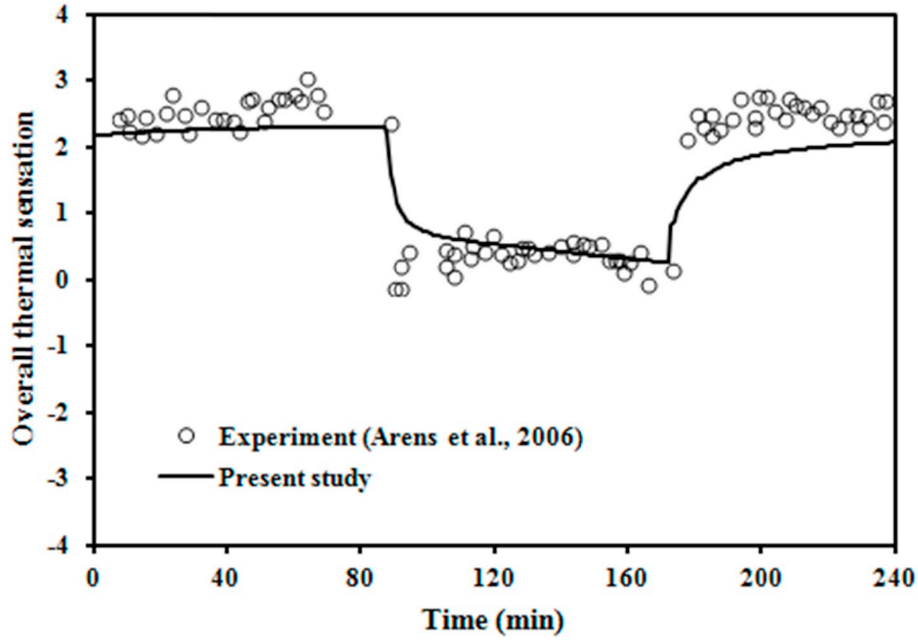

Fig. 6. Comparison of predicted whole body sensation with experimental data (Arens et al., 2006a, 2006b) under transient conditions.

with the empirical data (Fang et al., 2018). Also, the results suggest that the present model can predict the overall thermal sensation with higher accuracy than TSENS index (Gagge et al., 1971). Although the environmental conditions are assumed to be almost uniform in the above-mentioned cases, the TSENS index considers the same thermal/physiological properties and clothing insulation for all body segments. Indeed, the TSENS index ignores the influence of the local sensation of different body parts on the whole body's thermal sensation. However, in the present study, the local sensation of different body parts has been estimated taking into account the non-uniformity of the environment, clothing, and physiological properties. Thereafter, in the new method, the overall body thermal sensation has been evaluated using the local thermal sensations of various body parts.

Validation of the obtained overall thermal sensations under transient conditions has been performed against the experimental data of Arens et al. (2006a, 2006b). In this case, the air temperature suddenly changed from 34.3°C to 26.4 °Cand again from 26.4°C to 33.7°C. In Fig. 6, the predicted thermal sensation has been compared with the empirical data (Arens et al., 2006a, 2006b).

In the second case of transient conditions, the subjects with a metabolic rate of 1.15 met and initial warm thermal sensation are suddenly exposed to a temperature of 29.7°C and a relative humidity of 50%. In Fig. 7, the overall sensation obtained from present study has been compared with the experimental results of Arens et al. (2006a, 2006b).

According to Figs. 6 and 7, under transient conditions, the predicted

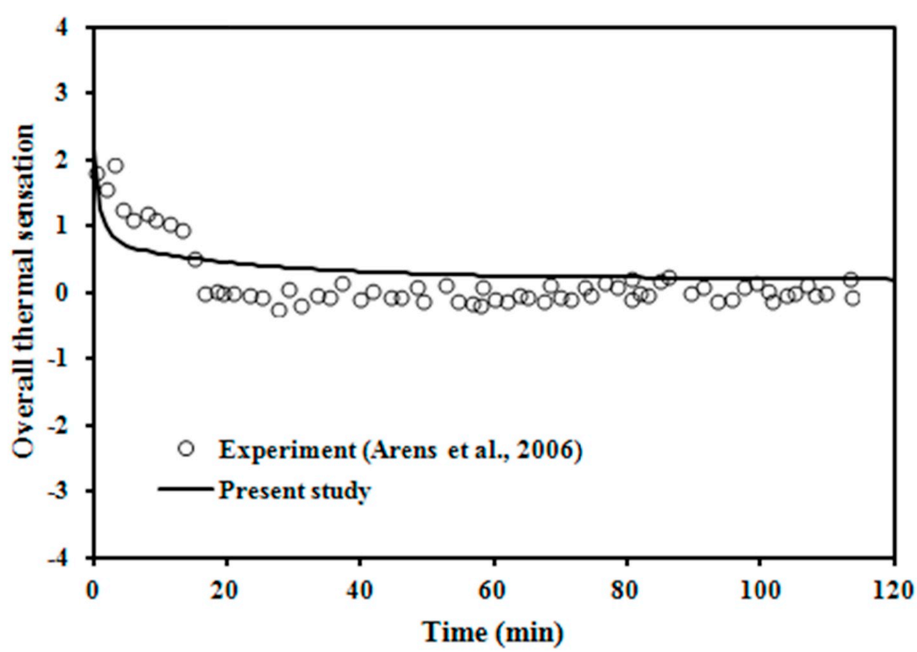

Fig. 7. Comparison of the predicted whole-body sensation with experimental data (Arens et al., 2006a, 2006b) under transient conditions.

results of whole-body sensation are in a good agreement with experimental data. On the other hand, the mean and maximum errors for the first case have been 0.3 and 1.02, and for the second case 0.26 and 0.49.

4. Conclusions

In non-uniform conditions, the whole body's thermal sensation is affected by the local sensation of various body parts. Therefore, in order to assess the overall body's thermal sensation, the local sensation of different body segments should be predicted. In our previous studies, a new local thermal response index (LTRESP) was introduced to assess the local sensations based on individual tissues TRs thermal responses. In the present study, in order to evaluate the overall body sensation, a new approach was proposed which involved coupling the LTRESP index and the UCB overall thermal sensation model. In this way, instead of using empirical data, the local thermal sensations obtained from LTRESP index were defined as the input data for the UCB model. Note that the overall body thermal sensation evaluated by the new method would be based on the cutaneous TRs response. The validation of the proposed method indicated a very good performance of the present method in predicting the whole body's thermal sensation under various environmental conditions. For non-uniform conditions, the new method revealed a mean absolute error of 0.21 and a maximum error of 0.51, with a mean absolute error of 0.20 and a maximum error of 0.30 under uniform conditions. Meanwhile, the new method offered a better performance than TSENS index in assessing the whole body's thermal sensation under uniform conditions. In general, the MSTB model, LTRESP index, and the new presented method could be used with acceptable accuracy to assess local temperature, local thermal sensation, and overall thermal sensation at different environments, such as environments with displacement ventilation systems, personalized ventilation systems, and environments with asymmetric radiant panels.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jtherbio.2019.05.027.

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