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Experimental study on thermal sensation of people in moderate activities

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ABSTRACT

The motivation of this study is to get better understanding about the real thermal sensations of people who undertake moderate activities. Experiments were conducted in a climate chamber. Sixteen subjects participated in two kinds of activities: treading in situ and up-and-down a step. Their metabolic rate, skin temperatures were measured. The subjects' thermal sensation votes, sweat feeling index and air movement preference were collected during experiments. The results showed that the PMV model overestimated subjects' thermal sensation for both activities. The analysis to sweat feeling index showed that subjects' thermal sensation was related to sweat activity. And the thermal regulation process of sweat had some impact on people's thermal sensation. Furthermore, the sweating process influenced mean skin temperature, which led to the decrease of neutral skin temperature at moderate activities. A linear relation was proposed to calculate the neutral skin temperature for different metabolic rate. The relation was compared with equations of Fanger and Gonzalez, which indicated that Fanger's equation strayed from the other two formulas when metabolic rate was above 2.5 met. Analysis about air movement showed that subjects expected higher velocities as activity was intensified.

1. Introduction

In modern society, people spend most of their time inside buildings. Building environment has great impact on people's health, comfort and productivity [1–3]. Thermal comfort studies are helpful to create favorable indoor climate, maintain productive thermal environment and keep reasonable energy consumption [4–6]. Most thermal comfort studies are focused on office buildings, classrooms or homes, in which people usually sit or take low level activities. Actually, people may undertake various activities indoors, like those who work on assemble lines or those who exercise inside buildings. With the increase of activity, the body heat production and thermal regulation process involved would be different from low activities [7]. And the thermal environment that makes people feel satisfied could not be the same.

The commonly used thermal comfort model is the PMV model [8]. The recommended activities for PMV model ranges from 0.8met to 4met [9]. Analyses of Humphreys and Nicol [10] on ASHRAE RP-844 showed that the accuracy of PMV varied according to metabolic rate (MR). The PMV model best predicted actual thermal sensation for activity levels below 1.4 met. Above 1.8 met, PMV could overestimate actual thermal sensation by up to one scale unit. This trend was also supported by analyses from other researchers [11,12]. Presently, most studies about human exercise concentrate on heat stress, physiological regulations and assessment [13–15]. The aim of such studies is to provide scientific guides for thermal protection and better understanding. And thermal comfort is seldom the focus because of the high intensity of activity or extreme climate involved. Although there are research works with a view to the effect of metabolic change on thermal sensation, they emphasize on transient subjective responses or on hot and humid conditions [16,17]. The purpose of this study was to investigate people's real thermal sensation at moderate activities in the range of 2 met to 5 met; and to get better understanding about the accuracy of PMV for higher level of activities.

As MR increases, the heat loss of body should be increased to keep thermal balance. Evaporative heat transfer by sweat is the most effective way in physiological regulation to achieve that balance. Changes in body heat production and heat loss will have some influence on skin temperature, which is one of the important parameters affecting thermal sensation [18,19]. Skin temperature has been used as a physiological index in predicting thermal sensation

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at low activities [20,21]. In this paper, mean skin temperature is also tested to figure out its impact on thermal sensation at higher activities.

2. Methodologies

The experiment was carried out in a climate chamber (L × W × H = 4 × 3 × 4.5 m), which was placed inside an air-conditioned room. And the air temperature inside the chamber could be controlled within ±0.5 °C.

2.1. Participants

A total of 8 male and 8 female college students (mean values ± standard deviation of age, 24.5 ± 2.45 years; height, 167.6 ± 8.32 cm; weight, 59.2 ± 10.66 kg) were recruited for the experiments. All subjects were healthy, non-smokers who were not taking any prescription medication. All protocols were approved by the university's ethics committee and conformed to the guidelines contained within the Declaration of Helsinki. Subjects were asked to avoid alcohol, smoking, and intense physical activity at least 24 h prior to each experimental session. All subjects were required to wear uniform clothes of T-shirt, walking shorts, socks, shoes and underwear (an estimated clothing insulation value of 0.36–0.4 Clo, we took 0.36 Clo in later analysis).

The sixteen subjects were assigned into 8 groups, each group comprised of two males or two females.

2.2. Design of experiments

To investigate human thermal sensation in laboratory, two kinds of exercise were introduced to simulate different activity levels. One was treading in situ (activity 1) with an average frequency of 80 steps per minute; another was up and down a step (20 cm high) (activity 2) about twenty-five times per minute. The estimated MR for the two activities was in the range of 2met to 5met, which fell into the classification of moderate MR and high MR in ISO 8996 [22] or the scope of moderate activity defined in physical activity [23].

Considering that air temperature was an important factor affecting thermal sensation [21,24], the experiments were carried under different air temperatures of 22 °C, 24 °C and 26 °C. When the air temperature was kept at 26 °C, people would feel a little hot if they took moderate activities. Increased air movement would be helpful to enhance heat loss and lower thermal sensation. To investigate subjects' expectation on air movement, variable-speed fan was used to generate air movement around the test area at 26 °C.

2.2.1. Design of questionnaires

During the experiments, the subjects were asked to assess their thermal environment for thermal comfort, air movement preferences and sweat feeling. Thermal sensation votes were based on the nine-point thermal sensation scale, see Fig. 1. Air movement preferences was scaled as −1, 0, and 1, which represented subjects' expectation of less air movement, neutral and more air movement respectively. Although sweat rate could not be tested in the experiments, people could judge about whether they sweated and how strongly they were sweating. The sweat feeling index (SFI) was introduced to investigate the influence of sweat activity on thermal sensation and skin temperature. SFI was scaled as 0, 1, and 2, which meant that the subject had no feeling of sweating, slight feeling of sweating and strong feeling of sweating respectively.

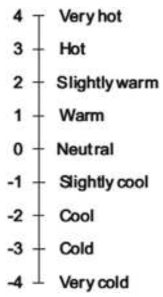


Fig. 1. Thermal sensation scale used in the experiments.

2.2.2. Arrangement and time schedule

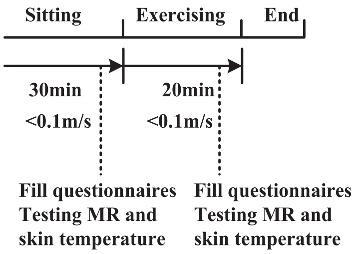
On arrival, subjects entered the chamber sitting for about 30min, and then filled the questionnaires. After that, they started to exercise as required. According to studies by T. Goto etc. [16], people's thermal sensation and skin temperature tended to be steady within 15–20min when metabolic rate changed. In another study by J. Toftum and R. Nielson [25], they arranged experiments in five consecutive 15-min periods and the subjects was exposed to mean air velocities increased step-by-step for given activity. Based on these references, in this study, the subjects were asked to keep exercising for 15min, and then filled the questionnaires. After that, their MR during exercise was tested. Each exercising condition lasted for about 20min. See Fig. 2(a).

At 26 °C, followed the previous procedure, the air velocity around the subjects' truncus was adjusted to 0.6 m/s and 0.9 m/s step wisely, and the subjects filled the questionnaires correspondingly, see Fig. 2(b). The air movement was adjusted by a variable-speed fan, which was located 2 m in front of the subjects.

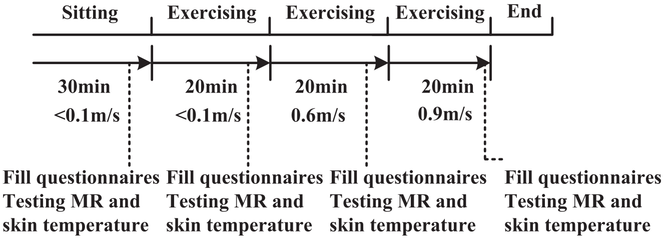
To be more explicit, the experimental conditions were shown in Table 1.

2.3. Physiological and physical measurements

Skin temperatures at five points were tested by thermistors (Pt 100 with precision of ±0.15 °C in the range of 0 °C to +50 °C) during the experiments. The five points were forehead, chest, upper arm, lower back and upper leg. Mean skin temperature (MST) was



(a) Time schedule at 22°C/24°C



(b) Time schedule at 26°C

Fig. 2. Time schedule of experiments.

Table 1
Experimental conditions.

Air temperature (°C)	Activities	Air velocity (m/s)
22	Activity 1	<0.1
	Activity 2	<0.1
24	Activity 1	<0.1
	Activity 2	<0.1
26	Activity 1	<0.1
		0.6
		0.9
	Activity 2	<0.1
		0.6
		0.9

calculated with the sum of products of local skin temperatures, with weighting factors of 0.15 for forehead, 0.19 for chest, 0.10 for arm, 0.19 for back and 0.37 for leg [26].

MR was tested by Vmax Encore Metabolic Cart (Sensor Medics Corp., California, USA) equipped with mass flow sensor, electro chemical cell, non-dispersive infrared thermopile (For mass flow sensor, the testing range is 0–16LPS and the flow accuracy is ±3% of reading or 0.25LPS, whichever is greater; for O_2 analyzer, the testing range is 0–100% and the accuracy is ±0.02%; for CO_2 analyzer, the testing range is 0–16% and the accuracy is ±0.02%; for barometric pressure transducer, the range is 300–800 mmHg and the accuracy is ±3 mmHg). To avoid the specific dynamic effect of food on MR, all subjects attended the experiment at least 1 h after meal.

Wall temperatures of the chamber were measured by thermocouples (T type with testing precision of ±0.5 °C) to calculate mean radiation temperature. The signals of thermistors and thermocouples were collected by data acquisition system (Agilent 34970A, HP Co, California, USA) during the experimental process. Air temperature, velocity and relative humidity were measured by multi-parameter ventilation meter (Model 8386, TSI Inco., Minnesota, USA. For temperature sensor, the testing range is −17.8–93.3 °C and the accuracy is ±0.3 °C; for relative humidity, the testing range is 0–95% and the accuracy is ±3%; for velocity, the testing range is 0–50 m/s and the accuracy is ±3.0% of reading or ±0.015 m/s, whichever is greater).

2.4. *Statistical analysis of environmental parameters*

The environmental parameters tested in the experiments were shown in Table 2.

To compare the data of different conditions, one-sample t test was followed by independent samples t test or paired-samples t test. The significance level was set to 0.05 ($P < 0.05$). SPSS 16.0 was used for statistical analysis.

3. Results

3.1. *Results of tested MR and calculation of heat production*

The average MR tested in all the experiments for sitting, activity 1 and activity 2 was shown in Fig. 3. The mean value for sitting was 1.16 met; for activity 1, it was 2.78 met and for activity 2 it was 4.87 met. The MR of males was 7–16% higher than that of females.

In thermal comfort evaluation, mechanical work accomplished must be considered. The body heat production is calculated by deducting mechanical work from MR. The mechanical work done by the muscles for a given task was often expressed in terms of the body's mechanical efficiency: $\mu = W/M$. It was unusual for μ to be more than 0.05 to 0.10; for most activities, it was close to zero. The mechanical efficiency for sitting and activity 1 was zero, for activity 2 it was estimated as 0.085 according to study by Zhang etc [27]. The average heat production for activity 2 would be 4.46 met. For sitting and activity 1, the heat production equaled to MR.

3.2. *Results of thermal sensation*

3.2.1. *Comparison of MTSV and PMV*

The subjects' mean thermal sensation vote (MTSV) in conditions that the air velocity was less than 0.1 m/s was shown in Fig. 4. The MTSV increased as temperature and heat production increased ($P < 0.01$). The MTSV was compared with the thermal sensation predicted by PMV model. For sitting, the prediction of PMV came closely to the MTSV in the three temperature conditions and the average deviation was only 0.23. The deviation increased as activity increased. The average difference between MTSV and PMV was 0.8 for activity 1, and 1.24 for activity 2. The results showed that the PMV model was quite accurate at low activities. However, it overestimated thermal sensation at higher activities and the deviation tended to increase as heat production increased ($P < 0.05$). For activity 2, the calculated PMV was beyond 3 at 24 °C and 26 °C, and

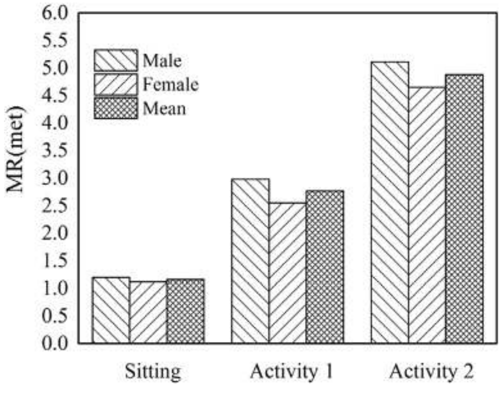


Fig. 3. Average MR for sitting and the two activities.

Table 2
Environmental parameters tested in experiments.

Tested environmental parameters		Experiment conditions		
		22 °C	24 °C	26 °C
Air temperature (°C)		22.2 ± 0.2	23.9 ± 0.3	26.1 ± 0.4
Relative humidity (%)		52 ± 1.9	54 ± 4.2	57 ± 3.5
Mean radiant temperature (°C)		22.7 ± 0.1	24.1 ± 0.1	26.1 ± 0.6
Air velocity (m/s)	<0.1	0.10 ± 0.05	0.08 ± 0.02	0.09 ± 0.03
	0.6	–	–	0.61 ± 0.04
	0.9	–	–	0.89 ± 0.06
Operative temperature (calculated,°C)	<0.1	22.4	24.0	26.1
	0.6	–	–	26.1
	0.9	–	–	26.1

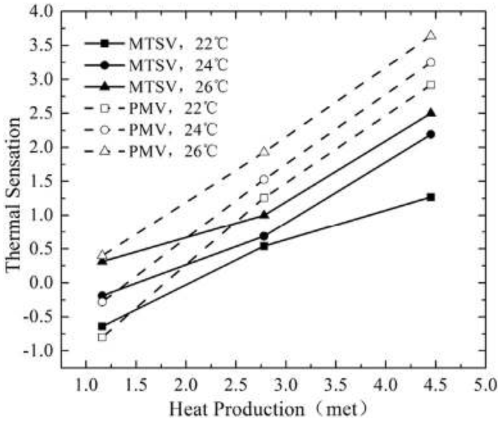


Fig. 4. Changes of MTSV and PMV with heat production.

such conditions exceeded the prediction range of PMV.

3.2.2. Effect of air movement on thermal sensation at 26 °C

The effect of air velocity (26 °C) on MTSV was shown in Fig. 5. As the prediction of PMV was quite accurate for sitting, we calculated it in accordance with the environment parameters of activity 1 and 2. The MTSV and calculated PMV decreased as velocity increased ($P < 0.05$). The calculated PMV for sitting decreased 1.5 scale when air velocity increased to 0.9 m/s, while for activity 1 and 2 the decline of MSTV was around 0.5 scale, which indicated that the cooling effect brought by air movement tended to be smaller for moderate activities.

3.3. Results on air movement preference

The statistics of air movement preference or air movement expectation (AE) at 26 °C was shown in Fig. 6. When air velocity was below 0.1 m/s, most subjects expected more air movement (AE>0). As velocity rose, the percentage of AE>0 decreased and the percentage of AE<0 increased. For activity 1, when air velocity was 0.6 m/s, 75% of the subjects expected no change of velocity (AE = 0). As velocity increased to 0.9 m/s, more subjects expected less air movement. This tendency implied that most people preferred to 0.6 m/s at activity 1. As velocity increased, too much air movement would cause draft risk and annoying effect that made people dissatisfied as stated by Fanger [28] and Xia et al. [29]. If took the subjects that selected AE = 0 as those who were satisfied with the air movement, the change of satisfaction rate with velocity for activity 1 could be regressed to a parabolic curve, as shown in Fig. 7. For activity 2, the proportion of AE>0 kept growing as velocity rose to 0.9 m/s, which meant that the subjects expected higher velocity as activity level increased. In this study, the maximum velocity tested was 0.9 m/s. The preferred velocity could not be analyzed for activity 2. Besides, the air movement experiments were all carried at 26 °C. Experiments about the effect of air temperature and other related parameters, like turbulence intensity and air movement directions, should be studied further.

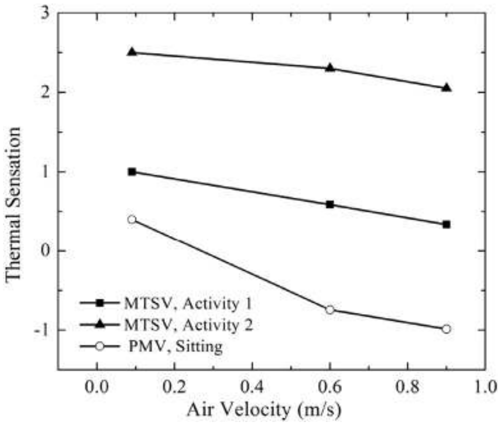


Fig. 5. Changes of thermal sensation with air velocity at 26 °C.

3.4. Results of MST

The MST of subjects in conditions that the air velocity was less than 0.1 m/s was shown in Fig. 8(a), and the change of MST with velocity at 26 °C was shown in Fig. 8(b). As skin temperature tended to be steady in about 15min, the average data of the last 5min of each condition were used in the analysis.

According to Fig. 8(a), the MST rose up when air temperature increased ($P < 0.01$). For the three activities, the MST of activity 1 was higher than sitting and activity 2. The body heat production of activity 1was larger than sitting, so it could be expected that skin temperature at activity 1 was higher than that of sitting. The heat production of activity 2 was also higher than activity 1, yet the skin temperature didn't increase further. Instead, the MST of activity 2 was a little lower than that of activity 1 at 22 °C and 24 °C. From Fig. 8 (b), the MST decreased as velocity increased ($P < 0.05$). And the difference of MST between activity 1 and 2 was quite small for each velocity condition at 26 °C.

3.5. Results of SFI

The SFI was helpful to understand the changes of MST in Fig. 8. Fig. 9 (a) showed the SFI in three activities (air velocity <0.1 m). It was quite obvious that SFI was positively related to activity level in different air temperature conditions ($P < 0.01$). The subjects' SFI was nearly to be zero at sitting and less than 1 at activity 1. When it came to activity 2, the SFI was above 1, which meant that people's sensation about sweating was stronger. The increased sweat rate would increase evaporative heat dissipation and thus decreased the skin temperature. Studies by Nielsen et al. [30] also found that subjects' thermal sensation increased during high metabolic work period while the skin temperature decreased.

According to Fig. 9(b), SFI dropped as velocity increased ($P < 0.05$). And the increased velocity could decrease MTSV, MST and SFI.

3.6. Analysis on neutral skin temperature

Individual thermal sensation vote and MST of all the experimental conditions were shown in Fig. 10. Thermal sensation vote was linearly related to MST for different activity level. The linear regression equations of MST with MTSV were as the following.

$$\text{For activity 1:}\ MST = 32.3 + 0.69MTSV \quad (R = 0.675, P < 0.0001) \tag{1}$$

$$\text{For activity 2:}\ MST = 30.7 + 0.86MTSV \quad (R = 0.858, P < 0.0001) \tag{2}$$

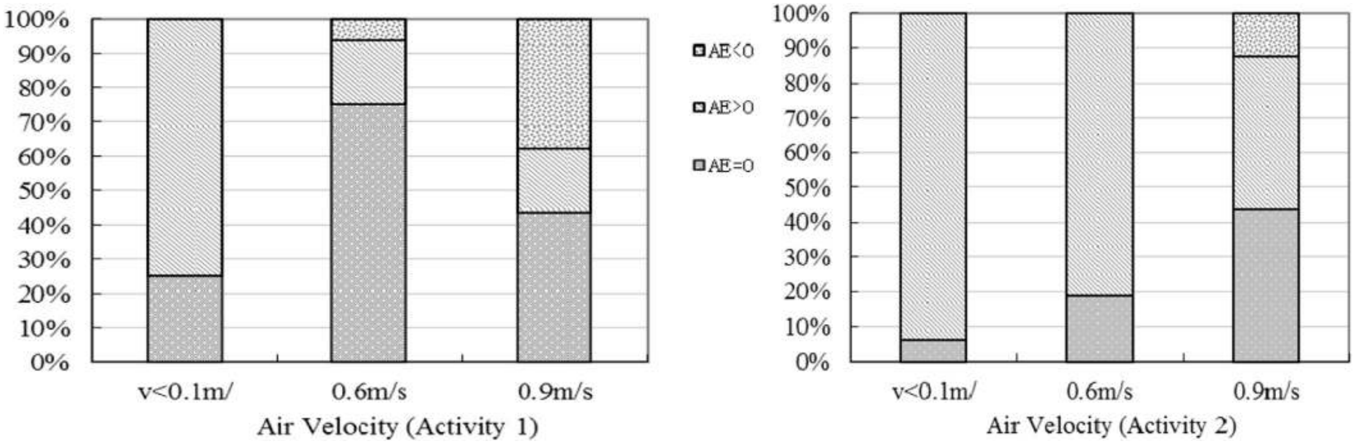


Fig. 6. Statistics of air movement preferences for the two activities at 26 °C.

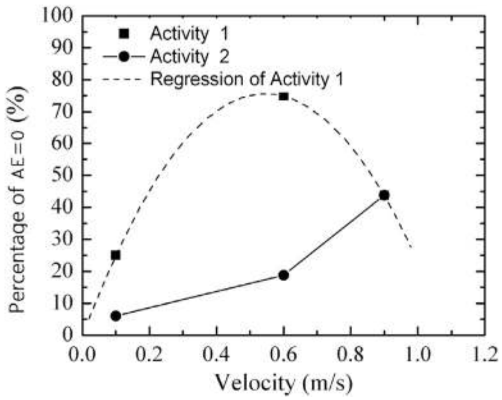
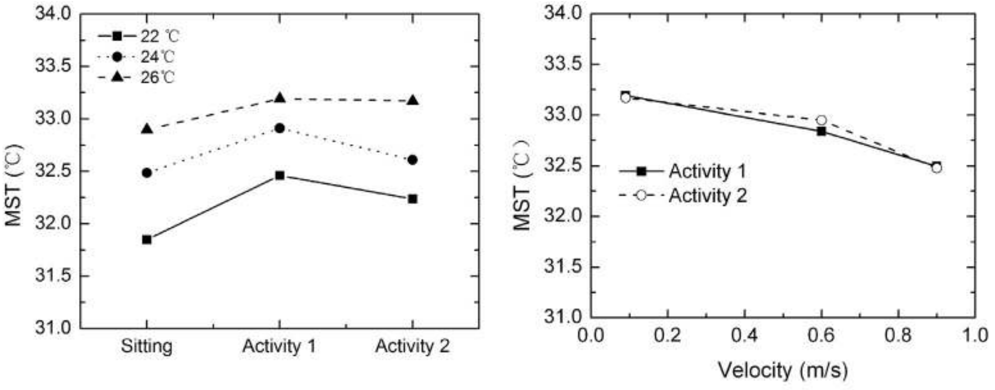


Fig. 7. Changes of air movement preference with velocity.



(a) Changes of MST with activities and air temperature (b) Changes of MST with velocity at 26℃

Fig. 8. Changes of MST with activities, air temperature and air movement.

$$\text{For sitting}: \ MST = 32.8 + 1.59MTSV \quad (R = 0.797, P < 0.0001) \qquad (3)$$

It should be noted that Equation (2) was fitted from data that thermal sensation was in the range of 1–3. This meant that all the experimental conditions in this study were on the warm side for activity 2. If let subjects under activity 2 feel neutral, we should either lower the air temperature or increase air movement further. Both the methods would decrease MST at the same time (see Fig. 8), which implied that the relation in Equation (2) could also be applicable around neutral conditions and it would not cause large deviation.

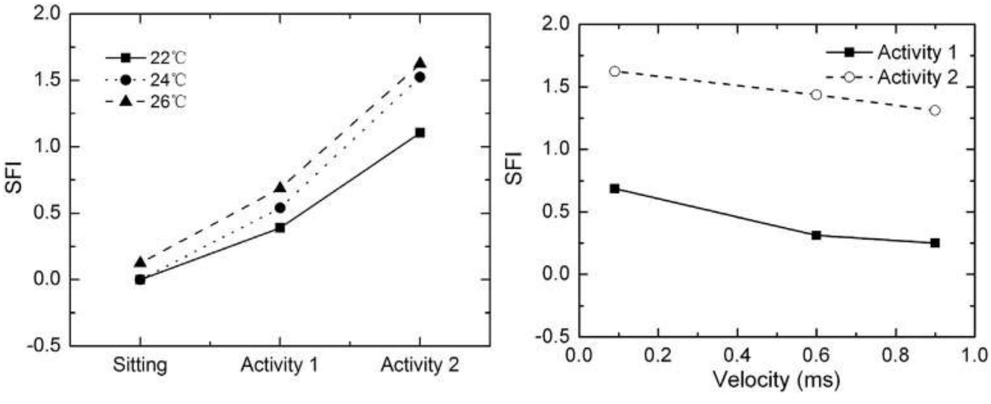
In these equations, if let MTSV be zero, the neutral skin temperature for each activity could be calculated, which was 32.8 °C for sitting, 32.3 °C for activity 1 and 30.7 °C for activity 2.

The neutral skin temperature decreased as activity level increased. According to analysis of SFI, this was due to the intensified sweating activity, and the increased evaporative heat transfer caused the decline of neutral skin temperature. This tendency was accordant with studies of Fanger [31] and Gonzalez [32]. And they both gave linear equations to calculate neutral skin temperature at different activities, see Equation (4) And (5).

$$\text{Fanger's equation}: \ t_{sk} = 35.7 - 0.0276 \times (MR - W) \qquad (4)$$

$$\text{Gonzalez's equation}: \ t_{sk} = 33.97 - 4.58 \times (Vo_2/Vo_{2.\max}) \qquad (5)$$

In these two equations, t_{sk} was neutral skin temperature, W was work done by human body, W/m^2, MR minus W was the heat production of human body, V_{O2} was oxygen consumption and $V_{O2.max}$ was maximal oxygen consumption. The ratio of $V_{O2}/V_{O2.max}$



(a)Effect of temperature and activity on SFI (b) Effect of velocity on SFI

Fig. 9. Changes of SFI with activities and velocities.

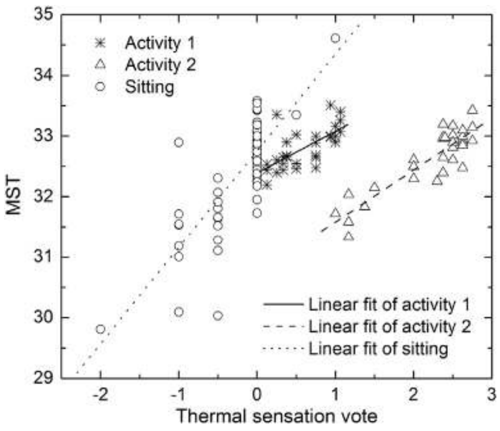


Fig. 10. MST and thermal sensation vote at different levels.

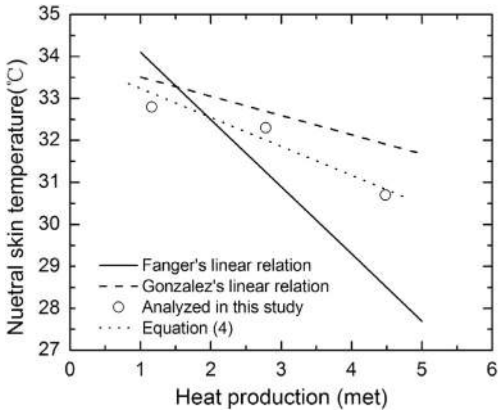


Fig. 11. Change of neutral skin temperature according to Equations (4)–(6).

represented the relative intensity of exercise. The oxygen consumption was related to MR directly and the maximal oxygen consumption was almost constant for specific groups. For example, the maximal oxygen consumption of the participants in the experiments, on account of their age and daily exercise, was equivalent to exercise intensity of 10 met.

Using the neutral skin temperatures calculated from Equations (1)–(3), a linear relation could be derived as

$$t_{sk} = 33.9 - 0.69(MR - W) \tag{6}$$

This linear relation was compared with Equations (4) and (5) in Fig. 11. It could be seen that Neutral skin temperature calculated by Equation (6) was close to Gonzalez's relation. The difference among the calculated neutral skin temperatures by these three relations were small (less than 1 °C) when heat production was below 2.5 met. The neutral skin temperatures calculated by Fanger's equation was much lower than that of the other equations as heat production was above 2.5 met. On account of that, Equation (6) and Gonzalez's equation were recommended when heat production was higher than 2.5 met.

4. Discussions

4.1. Effect of dynamic clothing insulation on the prediction of PMV

From the analysis, the prediction of PMV overestimated the real thermal sensation of subjects in moderate activities. The applicability of PMV model in such conditions was questioned. The PMV model was based on calculated thermal load by heat balance equation. Clothing insulation was an important factor in the calculation of heat loss. The estimated clothing insulation in PMV was based on data from static manikins. However, the body movement in activity 1 and 2 would cause changes in clothing insulation. Most types of clothing ensemble had openings (e.g. collars, cuffs) that allowed a certain air exchange with the environment. When people worked or exercised, the air change of the clothing would increase and affect the clothing insulation. This effect was called the "pumping effect". The pumping effect enhanced convective and evaporative heat exchange between human body and the environment [33,34]. The heat loss of human body would be larger than that calculated from static clothing insulation. In most studies, I_{corr} was used to correct the dynamic insulation. And studies had shown that I_{corr} was related to clothes thickness, fabric material, permeability and style [35]. Considering the clothes wore in the experiments, the calculated dynamic clothing insulation for activity 1 and 2 would be 0.30Clo and 0.26Clo, which was calculated by using correction equations from

Ref. [36]. Considering the dynamic clothing insulation, the calculated PMV decreased only 0.05–0.10 scale for activity 1 and for activity 2, which implied that the dynamic clothing insulation was not much effective in explain the deviation of PMV. Under moderate activities, the heat production and calculated heat load was beyond the prediction range of PMV.

4.2. Discussions about effect of air movement

In this study, analysis about the impact of velocity showed that people expected higher velocities as activity was intensified. It was natural that people, who were taking high level of activities and feeling warm or hot, would have a desire for cooling by air movement. Therefore, increasing air flow was effective to satisfy the needs of people undertaking moderate activities. Parkinson and de Dear [37] took a term—physiology of alliesthesia— to explain thermal pleasure of built environment, in which air movement applied on the warm side of the comfort zone (i.e. acceptably warm conditions) would carry a positive hedonic tone due to the corrective role of skin heat loss in offsetting the regulatory heat surplus. And for subjects experiencing mildly warmer-than-neutral whole-body sensations, air movement represents a desirable and sustainable mode of cooling. Toftum [38] once explained the effect of air movement in a review paper. Although, the acceptable velocities were up around 1.6 m/s in higher temperatures, the pressure on skin and general disturbance induced by the air movement may cause the air movement undesirable. At higher activities or warm environment, people expected or accepted higher velocities, yet the risk of draught sensation should be considered. Uğursal and Culp [39] studied the cooling effect of dynamic air movement and concluded that people could tolerate warm room temperatures even in high metabolic conditions provided that airflow was present with a certain pattern around them. According to these references, the expected air flow speeds and patterns that meet the demands of people under moderate activities needs further investigation.

4.3. Analysis about the use of SFI

In the experiment, a new index—SFI was adopted to represent the sweat activity. SFI was a subjective index like thermal sensation vote. The change of MST could be explained by g SFI. The relation of SFI with MTSV was further analyzed and shown in Fig. 12. It indicated that SFI was linearly related to MTSV for the two activities ($P < 0.001$), which meant that subjects' warm/hot thermal sensation was combined with their sensation of sweat. Sweating was a natural regulation process when people were in warm or hot environments. The investigation of SFI showed that the thermal regulation of sweat would, in a sense, affect subjects' sensation in warm side. As the actual sweat rate was not tested in this study, the relation between SFI and sweat rate could not be quantified. And as a subjective index, the applicability of SFI in evaluation thermal environment needs further studies.

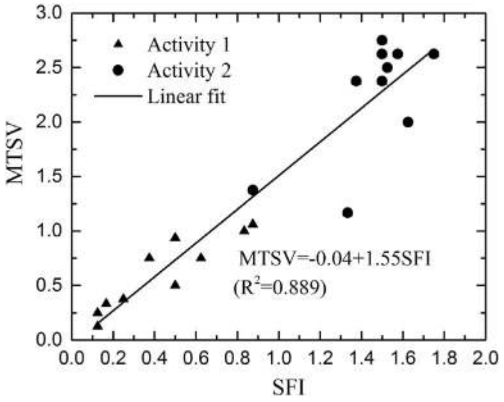


Fig. 12. Relations of SFI and MTSV.

5. Conclusions

In the present work, the effect of increased activity level on thermal sensation was investigated. The results showed that the prediction of PMV was accurate at sitting, yet it overestimated subjects' thermal sensation for both activity 1 and 2. So the PMV model had some deviation at higher activities and it might be improper to use PMV model to evaluate such conditions. Analysis on the effect of body movement on clothes insulation showed that dynamic clothes insulation was quite limited in explaining the overestimation of PMV. The analysis of SFI showed that subjects' thermal sensation was related to sweat activity. The sweat process enhanced evaporative heat loss, and also affected people's warm-side thermal sensation. Furthermore, the sweat regulation influenced mean skin temperature, which led to the decrease of neutral skin temperature at moderate activities. A linear relation was proposed to calculate the neutral skin temperature for different heat production activities. The relation was compared with equations of Fanger and Gonzalez, which showed that Fanger's equation strayed from the other two formulas as heat production was above 2.5 met. Analysis about air movement indicated that subjects expected higher velocities as activity was intensified and the risk of draught should be considered carefully.

It should be noted that sweat regulation had great impact on body thermal balance and thermal sensation when heat production increased. In order to fully understand the mechanism, it is necessary to test the actual sweat rate and amend the body heat transfer equations under such activities in future studies.

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