Experimental investigation into the effects of different metabolic rates of body movement on thermal comfort

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Abstract

Whether humans are in an idle state, walking, or engaged in another type of movement, metabolic activity is the key influential factor in comfort. However, there are a limited number of studies on the thermal comfort experienced by people while they walk, even though this state of motion is most common for daily commuting in modern societies. The predicted mean vote (PMV) model, the prevalent thermal comfort index, is restricted in terms of the accurate prediction of dynamic change in the thermal environment, such as that associated with walking. To study the thermal comfort of the walking process, a series of experiments were carried out in the badminton gym of Guangzhou University, in which 30 subjects were asked to walk at different speeds for 20 min and sit for 10 min. The thermal parameters were recorded during the experiments and the thermal perceptions of the subjects were collected. The results revealed a certain relationship between thermal sensation votes and physiological indexes. Typically, it takes the human body 3–5 min to reach a new metabolic level after walking, whereas it needs 4–5 min to return to a normal sedentary state from exercise. Moreover, surrounding airflow disturbances caused by walking enhances the heat transfer between the human body and surrounding thermal environment, leading to variations in thermal and air movement sensations. The neutral walking speeds which are affected by the outdoor thermal comfort experienced by the subjects while they were walking, were also determined.

Keywords*: thermal comfort; dynamic walking process; physiological indexes; metabolic rate;*

surrounding airflow disturbance

1. Introduction

Presently, for healthy living, there is a renewed interest in walking as opposed to driving in traveling short distances. In addition, thermal comfort, as one of the main factors affecting the quality of life and liveability, is attracting a great deal of attention in urban planning and design [1]. Whether comfortable indoor or outdoor spaces, thermal comfort is beneficial to the physical, environmental, economic, and social aspects of urban development [2]. Moreover, remarkable improvement due to continuous research is encouraged by the demand from the public for thermal comfort.

Over the past few decades, many studies have been conducted on indoor thermal comfort, but they concentrated mainly on static or stable motion. For instance, the predicted mean vote (PMV) model is the prevalent thermal comfort index. However, PMV was widely used for steady-state thermal environment evaluation [3]. Nicol and Humphreys noted that PMV was only suitable in a moderately steady environment [4]. Thus, in terms of accurate prediction of dynamic change in the thermal environment, the usage of PMV is restricted. In addition, the adaptive thermal comfort (ATC) model is another thermal comfort approach gaining attention, in which occupants are not only passive recipients of the environment but are also able to adapt and adjust actively to the surroundings through physiological acclimatisation, psychological adaptation, and behavioural adjustment [5,6,7,8]. The metabolic rate is a crucial physiological index for both PMV and ATC models.

The heat balance mechanism of the human body depends on the energy exchange between man and the environment. Energy metabolism is an essential part of the energy exchange. As a representative parameter for human energy metabolism, the metabolic rate has a significant influence on thermal sensation and comfort [9]. The prevalent metabolic rate estimation method in thermal comfort research and practice is called an ‘activity diary’, which regards the metabolic rate as a constant value based on the current and present activity level of an individual [10,11]. When calculating the PMV value, the metabolic rate obtained under a certain activity level is a constant value. However, while people are walking, their metabolic rates change over time. Thus, the method of assuming a constant value for the metabolic rate may not be sufficiently accurate to sustain precise thermal comfort modelling, as it does not consider individual variability in sex, age, and body mass index (BMI) [12,13]. Regardless, few studies consider dynamic changes in metabolic rate.

Because of the above-mentioned limitations, considerable research efforts exist for solving the problem of estimating the metabolic rate. For example, Hasan et al. [14] provided continuous feedback regarding the average metabolic rate by using wearable devices on building occupants. Havenith et al. [15] studied some personal factors in thermal comfort assessment and reported that the metabolic rates of ISO 8996 are not sufficiently accurate. Furthermore, to examine comfort under transient conditions, studies of the metabolic rate in the state of motion has emerged. In a field study on activity rates in an office environment, Colton and Larsen [16] examined the response of the metabolic rate to physical activity. These studies show that the change in metabolic rate during the exercise state does cause a change in the thermal sensation of the human body, some of which provide a method of reference for the estimation of the metabolic rate.

In addition, Schnorr et al. [17] studied variations in metabolic adaptation in the recovery period after exercise. In their study, Fabbri et al. [18] administered questionnaires to children to collect data to validate a proposed method for calculating metabolic rate from instantaneous heart rate. Ji et al. [19] proposed a new method to study human metabolic rate changes and thermal comfort in physical exercise by CO_2 measurement in an airtight chamber. These studies were concerned with the changes in the metabolic rate and thermal comfort during the dynamic process of instrument exercise. To date, there have studies on the thermal comfort of been few people walkers, though this state of motion is the most common for daily commuting in modern societies.

Therefore, to improve the thermal environment, based on the existing research [20], we study the thermal comfort under the dynamic process of human natural walking conditions. The study involves various external environmental factors, as well as the comprehensive effect of the regulation of the thermal comfort of the human body. Many studies [21, 22, 23, 24, 25, 26, 27, 28] have established models of human thermal comfort in an outdoor environment, and several of the these have been carried out regarding the mechanism of human body regulation [29]. To help urban planners develop sustainable development plans, outdoor thermal comfort prediction methods are constantly being proposed [30, 31], and various proposals for optimising outdoor thermal comfort have been presented [32, 33]. Usually, natural walking occurs outdoors. Considering that the outdoor environmental parameters—sunshine and shade, air temperature, wind speed, and direction—are highly variable and complex, the heat balance mechanism of the body is accordingly variable and complex [34, 35]. Therefore, to controlling some of the outdoor conditions that are usually difficult to control under working conditions, this research considers indoor natural ventilation without air conditioning. With this research plan, we moved outdoor research to a more stable indoor environment. Thus, the influence of most of the indoor environmental parameters is regarded as constant, and the only variable factor affecting the walking subjects is the air velocity. This study will pave the way for further expansion of outdoor research.

2. Methods

2.1 Experimental facility

The experiment was carried out in the badminton gym of Guangzhou University. Figure 1 shows the testing environment. During the experiment, three thermal comfort level recorders were set up in the middle and at both ends of the venue to measure the indoor environmental parameters. The measurements taken by the recorders placed near the subjects were carried out at a height of 1.1 m [36]. The main meteorological parameters were collected according to ASHRAE Standard 55-2017 [37].

2.2 Experimental design

2.2.1 Testing conditions

The experiment was carried out from March 2019 to April 2019, which is typically springtime in Guangzhou. According to the testing data, the range of indoor air temperature was 22 ± 2 ºC and the relative humidity was 80% ± 10%. Detailed parameters of the testing conditions are shown in Table 1.

2.2.2 Testing procedure

The experiment design focused on the dynamic change process for the auditory canal temperature, heart rates, metabolic rates, and heat storage at different exercise intensities together with the influence of all these factors on thermal comfort. Subjects were recruited to walk at an average velocity of 1.2 m/s, 1.4 m/s, 1.6 m/s, and 2.0 m/s in the gym. While the first two velocities were defined as slow-walking, the latter was defined as fast-walking. A metronome was used to keep subjects walking at the average velocities. During the experiments, subjects were asked to hold the wireless universal wind speed and temperature recorder at navel height. This is generally between 80 cm and 115 cm, with variations depending on the differences in subjects' heights.

We divided the experimental conditions into phases as follows. Phase 1, in which the subjects sat for 30 min, was designed as a control group and denoted the *preparing period*. During Phase 2, the *exercising period*, subjects were asked to walk for 20 min. In Phase 3, the rest period, subjects sat for 10 min to cool down. The specific experimental procedure is shown in Fig. 2.

2.2.3 Testing instrument

During the survey days, the indoor environmental parameters were recorded simultaneously. The environmental parameters measured included air temperature (T_a), relative humidity (RH), globe temperature (T_g), and air velocity (V_a). Furthermore, physiological indexes including auditory canal temperature and heart rate were also measured. The heart rate of the subjects was measured with a smart bracelet and auditory canal temperature was measured with an infrared thermometer. Auditory canal temperature was measured instead of body temperature. Many experiments investigating the feasibility of infrared tympanic thermometer suggested that rectal temperature was the best way to reflect the core temperature of the human body [38, 39]. Greenleaf et al. [38] suggested in his study that the extreme difference between rectal temperature and auditory canal temperature may reach 1°C. The research by Modell et al. [39] refuted the feasibility of infrared tympanic thermometer in clinical practice. Relatively speaking, the accuracy of temperature accuracy in clinical practice is relatively high, and Greenleaf et al. [38] have suggested that auditory canal temperature is the most appropriate way to reflect the mean body temperature. Furthermore, since rectal temperature measurement is difficult to achieve in dynamic testing, we finally chose to measure the auditory canal temperature, it is the most convenient and feasible method to measure the body temperature in this experiment. Detailed information on the instruments used in the experiment is given in Table 2.

2.3 Subjective questionnaire and physiological measurement

In total, 30 college-aged subjects in good health were recruited, composed of 18 males and 12 females. For both sexes, the average age and body mass index (BMI) were approximately 22.3 years and 19.2, respectively. The basal metabolic rate (BMR) of males was higher than that of females. Each subject participated in all three procedures at four different walking velocities. The experimental procedure was clarified to the subjects at the beginning of the experiment, and body parameters, such as height, weight, BMI, and BMR, were tested by a unified instrument. More detailed profiles are listed in Table 3. For each subject, the clothing insulation (*Iclo*) was also estimated. A list of clothing insulation for individual commonly worn garments is derived from the ASHRAE handbook [40]. During the experiment, the subjects were asked to dress in uniform, with long-sleeved shirts, thin trousers, socks, and sneakers, given that the thermal resistance of clothing was 0.61 clo.

The questionnaire used in the experiment [41] included two parts. The first part investigates the thermal sensation vote (TSV) and the air movement sensation vote (MSV) under the condition of the sit-in of subjects. The second part investigates not only the TSV and MSV during the exercising periods but also the physiological indexes at each testing moment. The scales of the subjective vote are shown in Table 4, found to be in accordance with the thermal environment in the ASHRAE Standard 55 [37] and ISO 7730 [42].

2.4 Data processing

2.4.1 The principle of metabolic rate measurement

Usually, the metabolic rate of the human body during a period can be calculated by the amount of O_2 inhaled and the amount of CO_2 exhaled [43]. In addition, the human metabolic rate can be measured [3] with a surrogate method, e.g., heart rate. The surrogate method is simpler and more convenient than the breathing method with inhaled O_2 and exhaled CO_2 concentrations. Therefore, in this study, the heart rate was measured in the subject as a proxy for the metabolic rate. The relationship between the measured metabolic rate and the heart rate was calculated by the following equation [3]:

$$M' = \frac{HR - HR_0}{RM} + M_0 \quad , \tag{1}$$

Where M' is the metabolic rate (W/m^2); M_0 is the metabolic rate in the inactive state (W/m^2); HR is the heart rate at the moment; HR_0 is the heart rate at rest, under thermally neutral conditions; and RM is the increase in the heart rate per unit of metabolic rate, which is stated by the following formula,

$$RM = \frac{HR_{max} - HR_0}{MWC - M_0}, \tag{2}$$

Wwhere HR_{max} is the maximum heart rate, $HR_{max} = 205-0.62 \times A$, and MWC is the maximum working capacity described in the following formulas:

$$MWC_{male} = (41.7 - 0.22 \times A) \times W^{0.666} (W/m^2) \tag{3}$$

$$MWC_{female} = (35.0 - 0.22 \times A) \times W^{0.666} (W/m^2) \tag{4}$$

Wwhere A is the age in years, and W is the weight in kg.

2.4.2 The principle of heat storage measurement

According to Equation (5–8), the heat storage (S) of the human body can be calculated [44, 45] as

$$S = M - W - R - C - E. \tag{5}$$

The value of R (radiant heat transfer), C (convective heat transfer), and E (evaporating heat transfer) can be described in the following formulas:

$$R = f_{cl} h_r (t_{cl} - t_r) \tag{6}$$

$$f_{cl} = \frac{1}{(1 + 0.155 \times (h_c + h_r) \times I_{cl})} \tag{6.1}$$

$$h_r = f_{rad} \varepsilon [(t_{cl} + 273.15)^2 + (t_r + 273.15)^2] \times [(t_{cl} + 273.15) + (t_r + 273.15)] \times 5.67 \times 10^{-8} \tag{6.2}$$

$$t_{cl} = 35.7 - 0.032M - 0.18 I_{cl} \{-3.4 \times 10^{-8} f_{cl} [(t_{cl} + 273.15)^4 - (t_r + 273.15)^4)] + f_{cl} h_c (t_{cl} - t_a)\} \tag{6.3}$$

where f_{cl} is the clothing area coefficient; h_r is the radiation heat transfer coefficient (W/(m^2. °C)); t_{cl} is the clothing surface temperature (°C); t_r is the mean radiant temperature (°C); f_{rad} is the correction coefficient of effective surface area of human body; ε is the surface emissivity of human body; I_{cl} is the effective thermal resistance of clothing (m^2 · kPa/W); and t_a is the air temperature (°C).

$$C = f_{cl} h_c (t_{cl} - t_a) \tag{7}$$

$$h_c = 8.6 v^{0.6} \tag{7.1}$$

where h_c is the convective heat transfer coefficient (W/(m^2 · °C)).

$$E = E_{sk} + (C_{res} + E_{res}) \tag{8}$$

$$E_{sk} = \omega (p_{sk} - p_a) R_{ecl} h_e \tag{8.1}$$

$$R_{ecl} = \frac{1}{(1 + 0.143 \times h_c \times I_{cl})} \tag{8.2}$$

$$LR = \frac{h_e}{h_c} \tag{8.3}$$

$$t_{sk} = 33.876 - 0.641M \tag{8.4}$$

$$C_{res} + E_{res} = 0.0014M(34 - t_a) + 0.0173M(5.87 - p_a) \tag{8.5}$$

where ω is the moisture index of skin; p_{sk} is the vapour pressure of water on the skin surface (kPa); p_a is the vapor pressure of water in air (kPa); R_{ecl} is the wet permeability coefficient of clothing; h_e is the coefficient of evaporating heat transfer (W/(m^2 · kPa)); and t_{sk} is the skin temperature.

2.4.3 Data analysis

During the experimental process, the mean thermal sensation vote (MTSV), mean air movement sensation vote (MMSV), auditory canal temperature, heart rate, and metabolic rate were recorded on a chart. The correlation between the variables was found using linear regression.

The experimental data were prepared and organised in Excel 2019, including the input of raw data, sorting, and averaging. All statistical analyses were performed using IBM SPSS Statistics 20, including the fitting of linear regression equations and the calculation of linear regression correlation index R^2. The figures and charts were created using IBM SPSS Statistics 20 and Origin 9 in accordance with the calculated thermal comfort responses.

3. Results

3.1 Variation in the thermal environment parameters

Table 5 shows the comparison of thermal environment parameters. In Table 5, the air velocity varied greatly. An insignificant difference exists in most of the parameters across the test states. Thus, the difference of thermal comfort at different walking speeds is not only related to the metabolism but also to the power of the disturbed air velocity around it. Therefore, in this investigation, the analysis of the disturbed air velocity at each walking speed was significant.

Fig. 3 shows the disturbance of the air velocity at different walking velocity levels. The average velocity of the natural wind was 0.13 m/s. With an increase in walking speed, the air velocity increases over that of natural wind. Under the condition of slow-walking, the disturbance effect of air velocity was similar, with the average value near 0.75 m/s. Under the condition of fast-walking, the air velocity disturbance caused by the walking speed of 2.0 m/s was stronger, with an average value of 1.11 m/s.

Fig. 4 shows the spectral distribution characteristic of each air velocity. From **Fig. 4**, the power spectral density of the natural wind was the smallest at the same frequency, and the power spectral density increased with an increase in the walking speed, which shows that the surrounding air velocity disturbance was caused by walking. The turbulent energy of the wind increased. The faster the walking speed was, the higher kinetic energy input was by disturbance.

3.2 Analysis of the subjective evaluations

During the experimental process, the MTSV (mean thermal sensation vote) and MMSV (mean air movement sensation vote) of the subjects were collected. **Fig. 5** shows the percentage of voting values in different walking states. The threshold of the voting value in the walking states can be shown intuitively. The results show that more than 50% of the votes correspond to the neutral sensation (0) during slow-walking. However, during fast-walking, the thermal sensation always exceeded the neutral sensation. The total of the percentages of +1, +2, and +3 during fast-walking was near 60%. Only a few people felt neutral. However, when subjects walked slowly, the total percentages of +1, +2, and +3 was only 30%. Thus, it was necessary to analyse the differences in the thermal sensation between the different walking velocities.

Fig. 6 shows the variation in MTSV (mean thermal sensation vote) with time. From Fig. 6, the slope of MTSV (mean thermal sensation vote) increased gradually under the condition of stable temperature and humidity and an increased walking speed. The faster the speed, the higher the final stable stage was. At different walking velocities, the MTSV (mean thermal sensation vote) increased from 0 to 15 min and tended to stabilise within 15–20 min. It soon returned to the initial sit-in state 10 min after walking.

Fig. 7 shows the variation in MMSV (mean air movement sensation vote) with time. At the beginning of the exercising period, MMSV (mean air movement sensation vote) was slightly weak. However, it increased rapidly from 0 to 1 min. At 1–20 min, MMSV (mean air movement sensation vote) dropped steadily and slightly. The values of the average slope "k" for each walking speed indicated the overall decreasing MMSV (mean air movement sensation vote) during the experiment. During the rest period, the MMSV (mean air movement sensation vote) of subjects with a walking speed of 2.0 m/s fluctuated greatly. At the beginning, the MMSV (mean air movement sensation vote) decreased rapidly to a slightly cool sensation (−1) before returning to approximately −0.5. The variation in MMSV (mean air movement sensation vote) under other conditions was similar, decreasing only slightly at first and finally stabilising at approximately −0.5.

To predict the variation in MTSV (mean thermal sensation vote) with walking speeds, a regression analysis between MTSV (mean thermal sensation vote) and walking speed was determined, as shown in **Fig. 8**. The R^2 of the fitting line was approximately 0.98, indicating that the MTSV (mean thermal sensation vote) and v have a strong linear relationship. **In Fig. 8**, we can see that when the walking speed reaches 1.03 m/s, the MTSV (mean thermal sensation vote) in the exercising period was zero, which indicated that in this walking condition, the thermal sensation was at neutral. For walking speeds between 0.65 m/s and 1.4 m/s, the MTSV (mean thermal sensation vote) was between ±0.5, which indicated that the thermal sensation was in the comfort zone within this walking speed range. If the environment is similar to the testing conditions, thermal sensation prediction at different walking speeds can be achieved.

3.3 Variations of physiological indices

Investigations have found that there are significant positive correlations between the heart rate and exercise intensity and between that and energy metabolism. Particularly in exercise, the load intensity increases gradually, and the energy metabolism demand increases. Thus, the heart rate should also increase [43]. Therefore, the heart rate can be used to reflect exercise intensity and human body metabolism. In addition, there is a positive correlation between the auditory canal temperature and metabolism. Hence, in the experiments, we recorded the heart rate and auditory canal temperature at each testing moment.

According to the measurement results, the range of heart rate was 60–110 bpm. The auditory canal temperature range was 36.2– 37.0 ºC. Under normal conditions, the heart rate fluctuations did not exceed 100 bpm. The fluctuations in the auditory canal temperature were usually not more than approximately 1 ºC [46, 47]. Thus, the relative changes in heart rate and auditory canal temperature as average values were analysed.

Fig. 9 shows the average changes in auditory canal temperature. In Figure 9(a), △T=T (time(i))-T (time(i=0)), while in Figure 9(b), △T=T (time(i))-T (time(i-1)). When the value of this moment is compared with the value of the previous moment, when the difference is within a certain range, it can be considered that a certain dynamic process becomes relatively stable. Therefore, in addition to comparing the value of each testing moment with the initial value, we also compare the value with the previous moment. As shown in Fig. 9(a), the subjects’ average auditory canal temperature showed a downward trend at each walking velocity. The faster they walked, the faster the average auditory canal temperature dropped. Many exercise experiments conducted in steady-state laboratories have shown that body temperature is elevated during exercise [48, 49, 50]. The difference between our walking test and these experiments is that the human body is subjected to a more pronounced airflow disturbance during walking. When the walking begins, the body's heat production cannot be quickly transmitted to the surface of the human body, which will cause a certain degree of delay. However, when people start to walk, the airflow disturbance is immediately generated, and this intensified convective heat transfer directly affects the surface of the subjects, which will enhance the heat dissipation of the human body, so the mean body temperature will first decrease. Then it rises because the body's heat production has been transmitted to most parts of the body. Fig. 9(b) shows that from 9 min to 20 min, regardless of walking speed, the difference between auditory canal temperatures was controlled to within ± 0.075 ºC, meaning that the temperature of the human body can remain relatively constant. During the rest period, the auditory canal temperature showed a state of rapid recovery. At a rest time of 10 min, the auditory canal temperature of the subjects had already returned to the initial state. At that time, $\Delta T_{\text{(compared with the initial value)}}$ was lower than 0.125 ºC. The subjects who had a faster walking pace experienced a faster recovery rate of the auditory canal temperature.

To predict the maximum range of decline possible in the subject auditory canal temperature, a regression equation for the maximum auditory canal temperature drop and walking speed was obtained by a fitting curve (**Fig. 10**). The results indicated that an excellent linear relationship existed between ΔT_{max} and v, with an R^2 of approximately 0.84. Based on the regression model, we can easily predict the mean maximum auditory canal temperature drop at a known walking speed.

Fig. 11 shows the average changes of heart rate. In Figure 11(a), △Heart rate=Heart rate (time (i))-Heart rate (time (i=0)). In Figure 11(b), △Heart rate=Heart rate (time (i))-Heart rate (time (i-1)). As shown in **Fig. 11(a)**, the heart rate rose rapidly in 1 min at the beginning of the exercising period. Then, the rate of rise slowed down. From **Fig. 11(b)** it can be seen that, from 3 to 20 min, the difference in the heart rate was kept stable in the range of ±10 bpm. The change in the heart rate was relatively constant at this time. During the rest period, the heart rate decreased rapidly within 5 min. After 10 min of rest, the heart rate returned to almost the same level as during the sit-ins, in which ΔHR was lower than 7 bpm.

To predict the maximum possible range of change in heart rate, a regression equation was fitted for the maximum heart rate change and walking speeds, as shown in **Fig. 12**. The R^2 of the fitted model was approximately 0.92, which means that ΔHR_{max} and V have a strong linear relationship.

Based on Equation (1–3), the average metabolic rate (M) of the subjects at each walking speed can be calculated. Fig. 13 shows the variation in the mean metabolic rate with time. ASHRAE Standard 55-2017 gives an estimate of the energy metabolic rate of adult men at different activity levels, with a metabolic rate of 2.6 met for walking at 1.2 m/s and a 3.8 met for walking at 1.8 m/s. Calculated by the difference method, the estimated metabolic values of 1.4 m/s, 1.6 m/s, and 2.0 m/s are 3.0 met, 3.4 met, and 4.0 met, respectively. Compared with the metabolic rate estimation table given in ASHRAE Standard 55-2017, we can see from **Fig. 13** that the actual mean metabolic rate is lower than the estimated value within 5 min of walking. By the fifth minute of walking, the actual average metabolic rate is close to the estimated value.

Fig. 14 shows the variation in heat storage with time. From **Fig. 14**, S appears to stay positive from the beginning to the end of the slow-walking condition. Meanwhile, under the fast-walking condition, S decreased to a negative value during the beginning of walking. At the beginning of 1 min, it turned to positive growth and then increased to positive values.

Fig. 9 to **Fig. 13** show that the auditory canal temperature of the subjects decreased rapidly when they began to walk in the first 5 min. However, the metabolic rate change showed an upward trend. The primary reason was that heat production in the human body had not covered the loss of heat from the enhancing convective heat transfer through the skin due to walking.

From 5 min to 20 min, except for the velocity of 2.0 m/s, the metabolic rate of the subjects for the other walking speeds maintained a small amount of fluctuation at a certain level. At this time, the body produced sufficient heat to compensate for the dissipation of heat from the surface of the skin. The body maintained a heat balance through the automatic heat balance mechanism.

As for the case of 2.0 m/s, the metabolic rate remained relatively stable from 5 to 11 min but continued to decline from 11 min to the end of the test. The reason for the decline was that 2.0 m/s was fast enough to increases the disturbance of wind speed around the skin, which accelerated the evaporation of sweat on the skin surface. When the sweat evaporated, the surface heat dissipation of the subjects increased. When the heat production equalled the heat dissipation, the human body achieved balance, and the body started the automatic regulation mechanism to reduce the metabolism. After the rest period, the metabolic rate of the subjects recovered steadily, equalling 0.25 met, which was lower than the metabolic value of the lower 1 met in the sit-in state. This indicated that the metabolic rate calculated by the heart rate was slightly lower than that of the actual condition.

Combined with the analysis of heat storage, MTSV, and MMSV, it was found that under the condition of slow-walking, the metabolic heat production increased rapidly, which exceeded the heat dissipation of the human body. In the case of fast-walking, at the beginning the wind speed disturbance clearly strengthened the heat dissipation on the surface of the skin and the metabolic heat production rate was not sufficient to offset the heat dissipation. Thus, the S volume showed a negative increase. The subjects briefly felt a slight cold when the walking test began with a significant drop in the auditory canal temperature. Then, due to the automatic regulation mechanism of the human body, the metabolic heat was gradually increased to balance the heat dissipation. The S began to show positive growth. As for the case of 2.0 m/s, from 11 min, S decreased rapidly. The perspiration rate on the skin surface of the subjects increased, along with the amount of heat removed by sweat evaporation. However, the metabolic rate remained basically unchanged, which led to a significant decrease in human heat storage. At the stage of S decline (within 11-15min), the MMSV (mean air movement sensation vote) had no significant change. However, the MTSV (mean thermal sensation vote) even increased steadily, which indicated that the subjective evaluation of human thermal comfort was not synchronized with the adjustment of mechanism regulating human heat balance. By 15 min, the sweat almost evaporated, and S showed an upward trend again.

To obtain the relationship between S and M, a curve regression model was fitted to analyse, shown in **Fig. 15**.

The S of the subjects at all walking speeds increased with $|\Delta T|$ except at 2.0 m/s. During the rest period, with a decrease in $|\Delta T|$, S also decreased gradually. In the case of 2.0 m/s, the relationship between S and ΔT in the exercising period could be categorized as two stages. The process of the first stage was similar to that of the other speed, and the relationship between $|\Delta T|$ and S can be described by a quadratic polynomial. When ΔT was lower than -0.37, there was a linear relationship between ΔT and S.

During the experimental period, a quadratic polynomial could describe the correlation between ΔT and S accurately. As a result, the variation in the auditory canal temperature was not synchronised with the variation in heat storage. Changes in auditory canal temperature exhibit hysteresis, occurring after a period of exercise. The primary reason is that during the walking process, the rise of heat storage under the adjustment of mechanism regulating human heat balance caused the increase of auditory canal temperature. This adjustment process takes some time to complete. Therefore, the growth of heat storage in exercising period was manifested by a rise in auditory canal temperature during the rest period.

During the experiment, the results revealed that there was a certain correlation between MTSV (mean thermal sensation vote) and S. Fig. 16 shows the relationship between MTSV (mean thermal sensation vote) and S. During the exercising period, a cubic polynomial function describes the correlation accurately. For the slow-walking case, S tends to be stable for an MTSV (mean thermal sensation vote) between 0 and 0.8. When fast-walking, S tended to be stable at the voting range of 0.5 to 1.5. Outside the stable region, S increased rapidly with MTSV. In addition, in the case of 2.0 m/s, when MTSV (mean thermal sensation vote) was between 2 and 3, it was impossible to fit the trend line because of the small amount of data and the significant fluctuation.

During the rest period, with the decrease in MTSV, S decreased as well. A quadratic polynomial could describe the correlation accurately.

4. Discussion

4.1 Effect of body heat balance regulation mechanism on thermal comfort

In the investigation, the physiological indexes (e.g., auditory canal temperature and heart rate) related to the heat balance regulation of the human body were tested and analysed. The heart rate method [18] was used to calculate the metabolic rate. Then, by comparison with the MTSV (mean thermal sensation vote) and MMSV, the thermal comfort of the human body at different walking speeds was found.

The results revealed that there were some differences in the changes of indexes in the heat balance mechanism. In the analysis of the physiological index, the change in heart rate was instantaneous, and the heart rate changed immediately after the start of exercises. However, changes in auditory canal temperature exhibit hysteresis, occurring after a period of exercise. Previous investigations have demonstrated that the heart rate was one of the surrogates for measuring the amount of exercise performed [51], as in this investigation. Therefore, it is considered that compared with the auditory canal temperature, the change in heart rate can more intuitively reflect the change in the metabolic rate of the human body.

Second, based on the analysis, it was easy to find whether a certain time difference exists between the subjective vote of thermal comfort and the regulation of the heat balance mechanism. The subjective evaluation of the human thermal comfort lagged behind the mechanism regulating human heat balance. When the body started to adjust, the subjective sensations had not changed. When the movement stopped, the influence of metabolic rate on the subjective sensations of thermal comfort continued for a while. Miao et al. [52] had found that the skin temperature in various parts of the human body, as well as the subjective psychological thermal sensation, increased with the gradual prolongation of exercise time. According to the Cheung [53] study of the correlation between thermal sensation and physiological reaction, during the all-around movements, appropriate physiological stress effect may reduce discomfort, and psychological intervention can slow the strain effect of the thermal sensation and prolong motor performance. Gagge [54] proposed a 2-node model of human thermal regulation, which clarified the separation in the skin temperature and thermal sensation. It was expressed as the "leading" of cold sensation and the "lag" of thermal sensation. Thus, the results of this investigation can be explained by the previous submissions from the Gagge findings.

Ji et al. [19] studied the human metabolic rate changes and thermal comfort in physical exercise by asking subjects to ride a spinning bike. They found that it usually took the human body 5–6 min to reach a new metabolic rate level after exercise begins and 7–9 min to return to a normal sedentary level from the exercising state. In this study, subjects were asked to walk at several speeds. It took the human body 3–5 min after walking to reach a new metabolic level. The metabolic level returned to a normal sedentary level from the exercising state in 4–5 min after walking stops. Comparing both investigations, the walking process reached a balanced metabolic level faster than did the riding process. It took less time to return to the initial state after stopping the exercise. Therefore, when setting the indoor environment parameters, full consideration of the active state of the human body for a period of time before entering the room should be considered. The occupant movement state in the room cannot be ignored, either.

Through the regression analysis of the experimental data, we obtained the relationship between the maximum change in the auditory canal temperature, the maximum change in the heart rate and the walking speed. Therefore, when the walking speed was known, the threshold of auditory canal temperature and heart rate could be quickly calculated. In the regression analysis of ΔT and S, the relationship between change in temperature and change in S was obtained, which directly reflected the lag in the temperature change. Through the regression analysis of MTSV (mean thermal sensation vote) and S, it was found that the change in S would affect the thermal sensation of the human body. It showed that when the exercise state was stable, S remained constant. However, the thermal perception continued to rise, which revealed the persistence of the effect of heat storage on the thermal perception. The state of motion at the previous moment was the cause of the change in the thermal sensation at this moment. Based on the above analysis, the influence of the continuous process of walking on thermal comfort should be given more attention when designing the interior environment, not just in the stable state of outdoor space.

4.2 Adaptability of PMV

In this investigation, MTSV (mean thermal sensation vote) was collected, and PMV was calculated. Fig. 18 shows the difference between MTSV (mean thermal sensation vote) and PMV under different experimental conditions. There were some deviations between TSV and PMV predictions. Fig. 17 showed that PMV was too high to predict the thermal sensation votes of the subjects during the exercising period for walking speeds of 1.2 m/s, 1.4 m/s, and 1.6 m/s. However, in the case of sit-in during the preparing period, the value of PMV and TSV was close, which indicates that PMV was more suitable for predicting the static state than the dynamic process [55].

It is well known that the PMV model is typically used to predict thermal sensations when human thermal equilibrium reaches a steady state after staying in a stable environment for a period of time [56, 57]. The reason is that PMV comprehensively considers the six factors of human activity level—clothing thermal resistance, air temperature, mean radiation temperature, air humidity, and air flow rate. During the calculation process, each factor adopts steady-state parameters, which are often assumed or simplified. For example, the metabolic intensity using the average value of a steady-state activity process during the calculation, and the dynamic process of the human body in real time cannot be displayed. However, TSV represents the real-time thermal sensation of the subjects during this dynamic walking period; thus, there must be a difference between the PMV and TSV values. From the results of this study, the PMV predicted value is higher than the actual voting value. For a walking speed of 2.0 m/s, the values of PMV and MTSV (mean thermal sensation vote) were not much different, as shown in Fig. 17. The primary reason may be the compensation of the surrounding air flow.

4.3 Effect of disturbance air velocity on thermal comfort

Just as people are sensitive to acoustic waves in a certain frequency range, the human body is also sensitive to airflow in a certain frequency range. Many studies [46, 47] have focused on the effects of airflow velocity and power spectral density on the human thermal sensation in a sit-in position. Luo et al. [58] found that it was possible for subjects to remain thermally comfortable under warm conditions of 28 °C and 30 °C, with air flows corresponding to the most suitable air velocity range of 0.4–0.6 m/s and 0.7–0.9 m/s, respectively. Xia et al. [59] found that the higher the pulsation intensity of the airflow was, the more likely it was to cause a blowing sensation, resulting in a model for predicting the probability of blowing sensation under an isothermal environment. However, so far, few investigations had concluded that air velocity had any effect on human thermal comfort when walking.

Ouyang et al. [60] summarised the difference between natural wind and steady-state airflow from the perspective of spectral characteristics, revealing that the β value of the natural wind (average negative slope of logarithmic power spectrum curves) is generally between 1.4 and 1.7. As shown in Fig. 4, the natural wind has a β value of 1.55, which is within the above range. When the walking speed increases, the β value decreases. With the increase in walking speed, the beta value decreases gradually. In Fig. 8, the MTSV (mean thermal sensation vote) falls in the comfort zone during slow-walking. At this time, the β values of the two velocities are 1.15 and 1.22, respectively, which is closer to the β values of the natural wind than that of the fast walking. Zhou et al. [61] demonstrated through climate chamber experiments that for a seated person, the simulated natural wind (β value is close to the natural wind) was more widely accepted by subjects than other forms of mechanical wind. The result of our walking experiment is consistent with this conclusion.

In addition, the results in this investigation show that the higher the walking speed was, the greater the disturbance of the surrounding air velocity was, the greater the energy of the surrounding air velocity to the human body was, and the greater the heat loss from the skin surface was.

Moreover, when the walking speed and walking time increased to a certain level, the air velocity had a certain compensation effect on the heat production of the human body. When the subjects walked at a speed of 2.0 m/s, the above compensation effect would occur. Obviously, the exercising state of the human body can affect the thermal comfort. The air velocity disturbance at different walking speeds was different from that of the heat balance. Therefore, when the indoor thermal environment parameters were set, the motion state of the human body in the room should be fully considered.

4.4 Limitation of this study

There are some limitations to this study that deserve discussion. Fig. 11(a) shows that when walking at a velocity of 2 m/s, the average change in heart rate has a small downward trend after 10 min. We search for the studies in the field of physiology, none of them reported a drop of heart rate during exercise. Buchheit et al. [62] and Boullosa et al. [63] studied the changes in heart rate during intense running, and the exercise intensity was significantly higher than walking strength of 2 m/s, which may explain why their experiments did not report a drop of heart rate. In addition, the experiments of Parak et al. [64] were performed in the laboratory, and the difference from this experiment was that there was no obvious influence of airflow disturbance caused by the walking process. We believe that the decline in heart rate for a period of time is caused by the automatic regulation mechanism of the body. When the sweat evaporated, the surface heat dissipation of the subjects increased. When the heat production equalled the heat dissipation, the human body achieved balance. The body started the automatic regulation mechanism and contracted the cardiovascular mechanism to reduce the metabolism. This process is reflected in the drop in heart rate [65]. Excluding the experimental error, we believe that the reasons for this downward trend need to be studied in the future.

5. Conclusions

To study the thermal comfort of the walking process, a series of experiments were carried out in the badminton gym of Guangzhou University, in which 30 subjects were asked to walk for 20 min at different levels of velocities and then were asked to remain sitting for 10 min. During the experiments, the thermal parameters were recorded. Meanwhile, the thermal perceptions of subjects were collected. The major findings of this investigation are as follows:

(1) With respect to the physiological indexes, the heart rate and auditory canal temperature can both reflect the level of human activity to a certain extent. However, the rate of change in the auditory canal temperature was delayed. The response rate of numerical changes is slower than that of heart rate.

(2) The variation in the metabolic rate should be fully considered in the prediction of thermal comfort. Typically, it took the human body 3–5 min after walking to reach a new metabolic level; meanwhile, the metabolic level can return to a normal sedentary level from the exercise state in 4–5 min after walking ceases.

(3) The changes in thermal sensation and physiological indexes of the human body were not synchronous. The changes in thermal sensation lagged the changes in physiological indexes.

(4) A constant velocity of human walking would cause a surrounding airflow disturbance. The airflow disturbance would have a strong effect on the thermal balance of the human body. The influence of airflow disturbance on human thermal comfort was stable after walking at the beginning of 3 min. Under the walking speed of 2 m/s, the effect of disturbed airflow could be divided into two stages. In the negative effect stage, with the passage of time, people felt the enhancement of blowing. In the positive effect stage, the perturbed airflow accelerated the sweat evaporation and the MTSV (mean thermal sensation vote) of the subjects decreased, continuing to decrease with the evaporation of sweat.

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Reference

[1] I. Golasi, F. Salata, E.L. Vollaro, M. Coppi, Complying with the demand of standardization in outdoor thermal comfort: A first approach to the Global Outdoor Comfort Index (GOCI) Building and Environment, 130 (2018) : 104-119.

[2] E. García-López, C. Heard, A study of the social acceptability of a proposal to improve the thermal comfort of a traditional dwelling Applied Thermal Engineering, 75 (22) (2015) : 1287-1295.

[3] P.O. Fanger, Thermal Comfort: Analysis and Application in Environmental Engineering, Danish Technology Press, Copenhagen, 1970.

[4] M.A. Humphreys, J.F. Nicol, The validity of ISO-PMV for predicting comfort votes in every-day thermal environments, Energy Build. 34 (6) (2002) : 667–684

[5] G.S. Brager, R.J. de Dear, Thermal adaptation in the built environment: a literature review, Heating Ventilating Air Conditioning 27 (1) (2011) : 83–96.

[6] R.J. de Dear, Developing an adaptive model of thermal comfort and preference, Ashrae Trans. 104 (1) (1998): 73–81.

[7] Z. Fang, S. Zhang, Y. Cheng, A.M.L. Fong, M.O. Oladokun, Z. Lin, H. Wu, Field study on adaptive thermal comfort in typical air conditioned classrooms, Building and Environment 133 (2018) : 73-82.

[8] Z. Fang, X. Feng, J. Liu, Z. Lin, C.M. Mak, J. Niu, K.T. Tse, X. Xu, Investigation into the differences among several outdoor thermal comfort indices against field survey in subtropics, Sustainable Cities and Society 44 (2019): 676-690.

[9] F. Formenti, D. Constantinteodosiu, Y. Emmanuel, et al., Regulation of human metabolism by hypoxia-inducible factor, in: Proceedings of the National Academy of Sciences of the United States of America 107(2010) : 12722–12727.

[10] ISO, EN ISO 8996: Ergonomics of the Thermal Environment — Determination of Metabolic Rate, International organization for Standardization, Geneva, 2004.

[11] Z. Fang, Z. Lin, C.M. Mak, J. Niu, K.T. Tse, Investigation into sensitivities of factors in outdoor thermal comfort indices, Building and Environment 128 (2018) : 129-142.

[12] S. Haddad, P. Osmond, S. King, Metabolic rate estimation in the calculation of PMV for children, Cutting Edge, International Conference of the Architectural Science Association, 2013.

[13] G. Ma., X. Ding, Impact of metabolic rate on human thermal comfort, Constr. Energy Conserv. 7 (2009) : 37–38.

[14] M.H. Hasan, F. Alsaleem, M. Rafaie, Sensitivity study for the PMV thermal comfort model and the use of wearable devices biometric data for metabolic rate estimation, Build. Environ. 110 (2016) : 173–183.

[15] G. Havenith, I. Holmér, K. Parsons, Personal factors in thermal comfort assessment: clothing properties and metabolic heat production, Energy Build. 34 (6) (2002) : 581–591.

[16] T.F. Colton, E. Larsen, Exercise physiology: the response of metabolic rate to physical activity, in: Proceedings of the 23rd Workshop/Conference of the Association for Biology Laboratory Education (ABLE) 23 (2002) : 235–254.

[17] J.D. Schnorr, G. Dörner, F. Stahl, et al., Human heat balance during post exercise recovery: separating metabolic and nonthermal effects, Am. J. Physiol. 294 (2) (2008) : 1586–1592.

[18] K. Fabbri, Indoor Thermal Comfort perception: A questionnaire Approach Focusing On Children, Springer, New York City, NY, USA, 2015.

[19] W. Ji, M. Luo, B. Cao, Y. Zhu, Y. Geng, B. Lin, A new method to study human metabolic rate changes and thermal comfort in physical exercise by CO2 measurement in an airtight chamber, Energy and Buildings 177 (2018) : 402-412

[20] K. George, H.A. Flocas, M. Andreas, Dynamic modeling of human thermal comfort after the transition from an indoor to an outdoor hot environment International Journal of Biometeorology 59 (2015) : 205-216.

[21] Z. Fang, X. Feng, X. Xu, X. Zhou, Z. Lin, Y. Ji, Investigation into outdoor thermal comfort conditions by different seasonal field surveys in China, Guangzhou, International Journal of Biometeorology 7 (2019) : 1-12.

[22] Z. Fang, Z. Lin, C. M. Mak, J. Niu, K.T. Tse, Investigation into sensitivities of factors in outdoor thermal comfort indices. Building and Environment 128 (2018) :129-142.

[23] W. Liu, D. Yang, X. Sheng, P. Yang. Indoor clothing insulation and thermal history: A clothing model based on logistic function and running mean outdoor temperature. Building and Environment 135 (2018) : 142-152

[24] W. Liu, W. Zhong, P. Wargocki. Performance, Acute Health Symptoms and Physiological Responses During Exposure to High Air Temperature and Carbon Dioxide Concentration. Building and Environment 114 (2017) : 96-105

[25] D. Yang, J. Xiong, W. Liu. Adjustments of The Adaptive Thermal Comfort Model Based on The Running Mean Outdoor Temperature for Chinese People: A Case Study in Changsha China. Building and Environment 114 (2017) : 357-365

[26] Lai, D., Chen, C., Liu, W., Shi, Y. and Chen, C., An ordered probability model for predicting outdoor thermal

comfort. Energy and Buildings 168 (2018) : 261-271.

[27] D. Lai, W. Liu, T. Gan, K. Liu, Q. Chen, A review of mitigating strategies to improve the thermal environment and thermal comfort in urban outdoor spaces. Science of The Total Environment661 (15) (2019) : 337-353

[28] D. Lai, C. Chen, 2019b. Comparison of the linear regression, multinomial logit, and ordered probability models for predicting the distribution of thermal sensation. Energy and Buildings 188 (2019b) : 269-277.

[29] A. Zhang, Y. Sun. The integral regulation of the overall view and the steady state of the human body. Journal of Shaanxi Chinese Medical College 26 (2) (2003) : 16-17.

[30] Y. Du, C.M. Mak, T. Huang, J. Niu, Towards an integrated method to assess effects of lift-up design on outdoor thermal comfort in Hong Kong. Building and Environment125 (2017) : 261-272.

[31] D. Lai, C. Chen, W. Liu, et al. An Ordered Probability Model for Predicting Outdoor Thermal Comfort. Energy and Buildings 168 (2018) : 261-271

[32] Y. Du, C.M. Mak, Y. Li. A multi-stage optimization of pedestrian level wind environment and thermal comfort with lift-up design in ideal urban canyons. Sustainable Cities and Society 46 (2019), 101424.

[33] A. Chatzidimitriou, S.Yannas, Street canyon design and improvement potential for urban open spaces; the influence of canyon aspect ratio and orientation on microclimate and outdoor comfort. Sustainable Cities and Society 33 (2017) : 85-101.

[34] M. Xu, B. Hong, R. Jiang, L. An, T. Zhang, Outdoor thermal comfort of shaded spaces in an urban park in the cold region of China. Building and Environment 155 (2019) : 408-420.

[35] Y. Xie, T. Huang, J.Li, J. Liu, C. M. Mak. Z. Lin, Evaluation of a multi-nodal thermal regulation model for assessment of outdoor thermal comfort: Sensitivity to wind speed and solar radiation. Building & Environment 132 (2018) : 45-56.

[36] ISO 7726, Ergonomics of the thermal environment – Instruments for measuring physical quantities (1998).

[37] R.A. Engineers ASHRAE Handbook: Fundamentals (2017).

[38] J. E. Greenleaf, B. L. Castle. External auditory canal temperature as an estimate of core temperature. Journal of Applied Physiology 32(2) (1972): 194-198.

[39] J.G. Modell, C.R. Katholi, S.M. Kumaramangalam, E.C. Hudson, D. Graham. Unreliability of the infrared tympanic thermometer in clinical practice: a comparative study with oral mercury and oral electronic thermometers. Southern medical journal, 91 (7) (1998) : 649-654.

[40] ANSI/ASHRAE Standard 55-2017: Thermal Environmental Conditions for Human Occupancy American

Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, Georgia (2017).

[41] ISO, International Standard 7730, Ergonomics of the Thermal Environment – Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria International Standard Organization, Geneva (2005).

[42] Y. Nishi, Measurement of thermal balance of man. Studies in Environmental Science 10 (1981) : 29-39.

[43] W. Li, Y. Zhang, L. Zhang, et al., The research of the sport burden grade standard corresponding to the heart rate, Nat. Sci. J. Harbin Normal Univ. 24 (5) (2008) : 99–102.

[44] T. Sakoi, T. Mochida, Y. Kurazumi, K. Kuwabara, Y. Horiba, S. Sawada, Heat balance model for a human body in the form of wet bulb globe temperature indices. Journal of Thermal Biology 71 (2018) :1-9.

[45] H. Wang, S. Hu, Experimental study on comfortable skin temperature under sweating condition. Heating Ventilating & Air Conditioning 5 (2014) : 110-113.

[46] Z. Fang, H. Liu, B. Li, X. Du, A. Baldwin, Investigation of the effects of temperature for supplied air from a personal nozzle system on thermal comfort of air travelers, Building and Environment 12 (2018) : 82-97.

[47] W.L. Kenney, J. Wilmore, D. Costill, Physiology of Sport and Exercise (sixth ed.), Human Kinetics, Champaign, IL (2015).

[48] C. Byrne, C. L. Lim, The ingestible telemetric body core temperature sensor: a review of validity and exercise applications. British journal of sports medicine 41 (3) (2007) : 126-133.

[49] B. Ekblom, C.J. Greenleaf, J.E. Greenleaf, L. Hermansen. Temperature regulation during exercise dehydration in man. Acta Physiologica Scandinavica 79 (4) (1970) : 475-483.

[50] B. Saltin, L. Hermansen. Esophageal, rectal, and muscle temperature during exercise. Journal of applied physiology 21 (6) (1966) : 1757-1762.

[51] Y. Zhu, X. Ruan, Z. Xu, X. Tian, E. Zheng, Research for the Important Relationship Between Activity Measurement and Heart Rate. Medical equipment 06 (2003) : 5-7.

[52] M. Miao, H. Lu, M. Cheng, Body surface temperature change and subjective thermal sensation assessment before and after exercise. Journal of Textile Research 4 (2018) : 39-45.

[53] S.S. Cheung, Interconnections between thermal perception and exercise capacity in the heat. Scandinavian journal of medicine & science in sports 20 (2010) : 53 – 59.

[54] A. P. Gagge, Rational temperature indices of man's thermal environment and their use with a 2-node model of his temperature regulation. Federation proceedings 32 (5) (1973).

[55] P.O. Fanger, J. Toftum, Extension of the PMV model to non-air-conditioned buildings in warm climates, Energy Build. 34 (6) (2002) : 533–536.

[56] B.W. Jones, Capabilities and limitations of thermal models for use in thermal comfort standards, Energy Build. 34 (6) (2002) : 653–659.

[57] R. Maiti, PMV model is insufficient to capture subjective thermal response from Indians, Int. J. Ind. Ergon. 44 (3) (2014) : 349–361.

[58] M. Luo, J. Yu, Y. Yang, O. Qin, Y. Zhu. Application of dynamic airflow on split air conditioning unit and its impacts on human thermal comfort: isothermal condition. Heating Ventilating & Air Conditioning 5 (2014).

[59] Y. Xia, J. Niu, R. Zhao, J. Burnett, Effects of turbulent air on human thermal sensations in a warm isothermal environment. Indoor Air (Print), 2000,10 (4).

[60] Q. Ouyang, W. Dai, H. Li. Study on dynamic characteristics of natural and mechanical wind in built environment using spectral analysis. Building and Environment 41 (2006) : 418-426.

[61] X. Zhou, Q. Ouyang, G. Lin, et al. Impact of dynamic airflow on human thermal response. Indoor air 16 (5) (2006) : 348-355.

[62] M. Buchheit, R. Solano, G.P.Millet. Heart-rate deflection point and the second heart-rate variability threshold during running exercise in trained boys. Pediatric exercise science 19 (2) (2007) : 192-204.

[63] D.A. Boullosa, E.S. Barros, S. Del Rosso, F.Y. Nakamura, A.SLeicht. Reliability of heart rate measures during walking before and after running maximal efforts. International journal of sports medicine 35 (12) (2014): 999-1005.

[64] J. Parak, I. Korhonen. Evaluation of wearable consumer heart rate monitors based on photopletysmography. In 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (2014) : 3670-3673).

[65] W. I. Cranston. Temperature Regulation. Surgery 24 (12) (1941) : 446-451.

Table

Table 1. Detailed information of testing condition

Classification	Air temperature T_a (°C)	Relative humidity RH (%)	Black globe temperature T_g (°C)	Air velocity v (m/s)
Max. value	24.14	84.15	24.20	1.22
Min. value	20.72	74.8	20.81	0.00
Average value	22.10	79.13	22.19	0.16

Table 2. Measurement instruments of this experiment.

Instrument	Type	Parameter	Measuring Range	Accuracy	Sampling Rate (s)
Thermal comfort level recorder	SSDZY-1	T_a (°C)	−20 to 80 °C	±0.3 °C	2
		RH (%)	0.01–99.9% RH	±2% RH (10–90% RH)	2
		T_g (ºC)	−20 to 80 °C	±0.3 °C	2
Wireless universal wind speed and temperature recorder	WFWZY-1	V_a (m/s)	0.05–5.00 m/s	5% ± 0.05% m/s	2
Smart bracelet	3XMSH05HM	HR (bpm)	30–250 bpm	± 3 bpm	2
Infrared thermometer	TB-300	T (°C)	32.0–42.2 °C	± 0.2 °C	1

Table 3. Detailed information of subjects.

Gender	Sample size	Age (y)	Height (cm)	Weight (kg)	BMI	BMR
Male	18	22.5 ± 1.5	175.3 ± 5	66.0 ± 8	19.3 ± 1.5	1481.3 ± 149.2
Female	12	21.5 ± 2.5	161.0 ± 3	50.5 ± 1.5	19.0 ± 1.3	1197.0 ± 20.0
Average	-	22.3	172.0	58.3	19.2	1339.1

Table 4. Subjective vote scale.

Thermal sensation	Blowing feeling	Thermal preference	Humidity preference	Acceptability
−3 cold	−3 much too strong			
−2 cool	−2 too strong			
−1 slightly cool	−1 slightly strong	−1 cooler	−1 lower	−1 unacceptable 1 acceptable
0 neutral	0 just right	0 no change	0 no change	
+1 slightly warm	+1 slightly week	+1 warmer	+1 higher	
+2 warm	+2 too week			
+3 hot	+3 much too week			

Table 5. Comparison of thermal environment parameters.

Classification		Air temperature T_a (°C)			Relative humidity RH (%)			Black globe temperature T_g (°C)			Air velocity v (m/s)		
		Max.	Min.	Average	Max.	Min.	Average	Max.	Min.	Average	Max.	Min.	Average
Stable state		24.14	20.72	22.10	84.15	74.80	79.13	24.20	20.81	22.19	0.22	0.08	0.13
Walking speed	1.2 m/s	24.03	20.72	22.30	86.30	74.80	80.47	24.10	20.78	22.49	0.99	0.49	0.79
	1.4 m/s	23.88	21.24	22.16	81.26	77.10	79.69	23.91	21.54	22.34	0.97	0.40	0.81
	1.6 m/s	24.09	21.54	22.67	87.60	76.10	77.98	24.20	21.83	22.79	1.13	0.49	0.87
	2.0 m/s	24.14	21.61	22.24	84.15	73.68	76.24	24.21	20.81	22.03	1.40	0.38	1.11

Figures

Fig. 1 Testing site

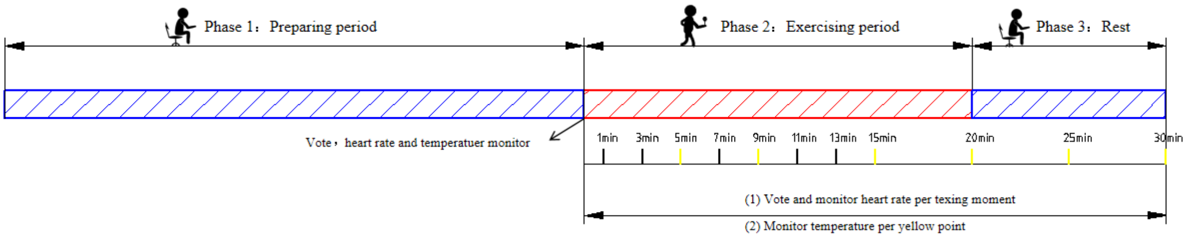


Fig. 2. Experiment procedure

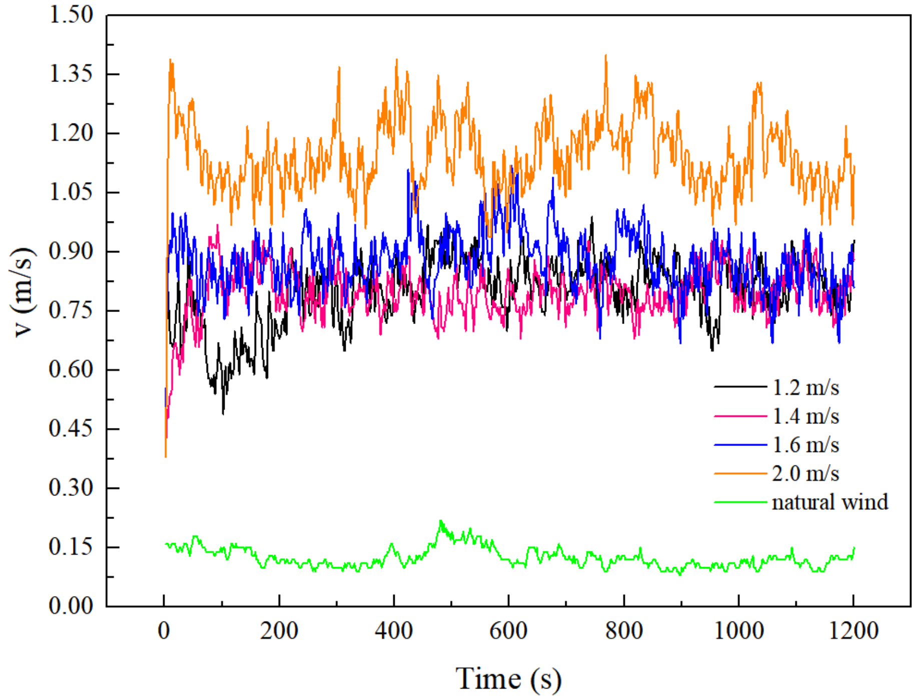


Fig. 3. The disturbance air velocity.

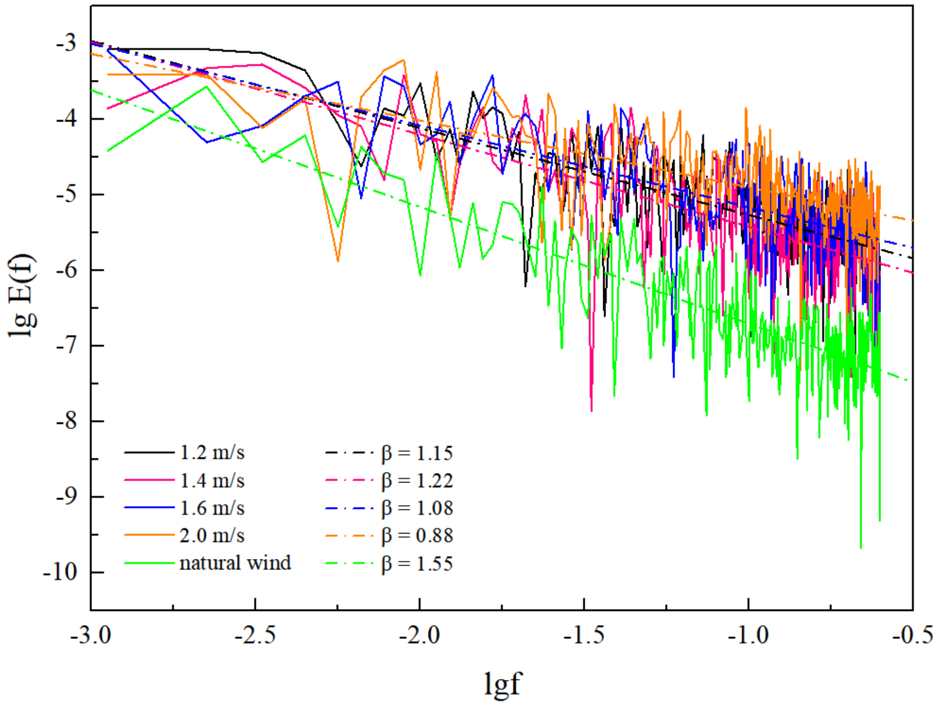


Fig. 4. The spectral distribution characteristic.

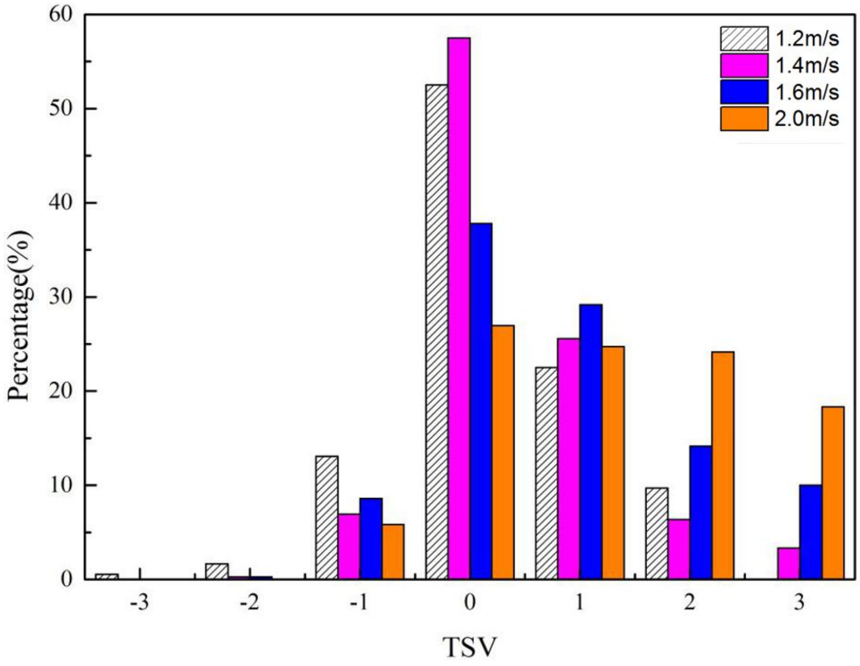


Fig. 5. The percentage of different voting values.

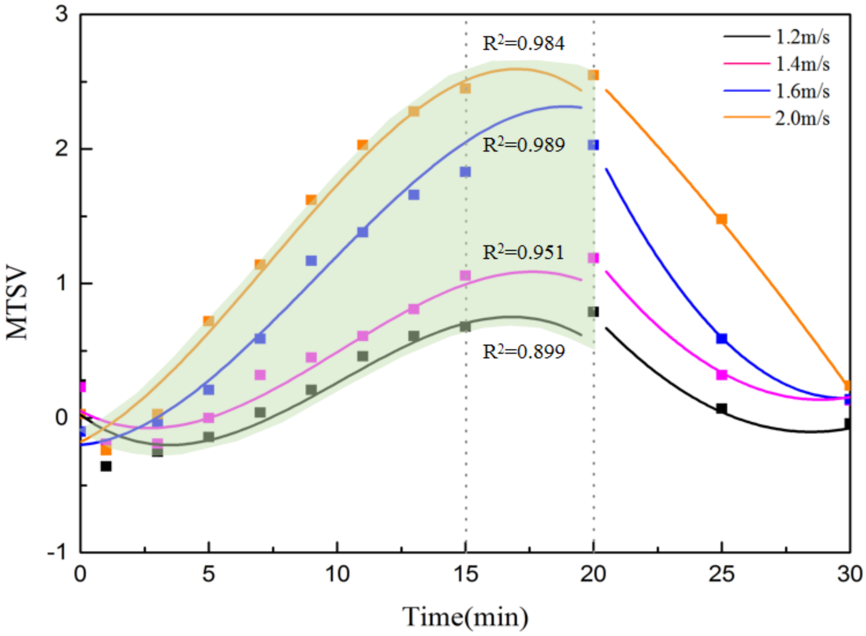


Fig. 6. The variation of MTSV (mean thermal sensation vote) with time.

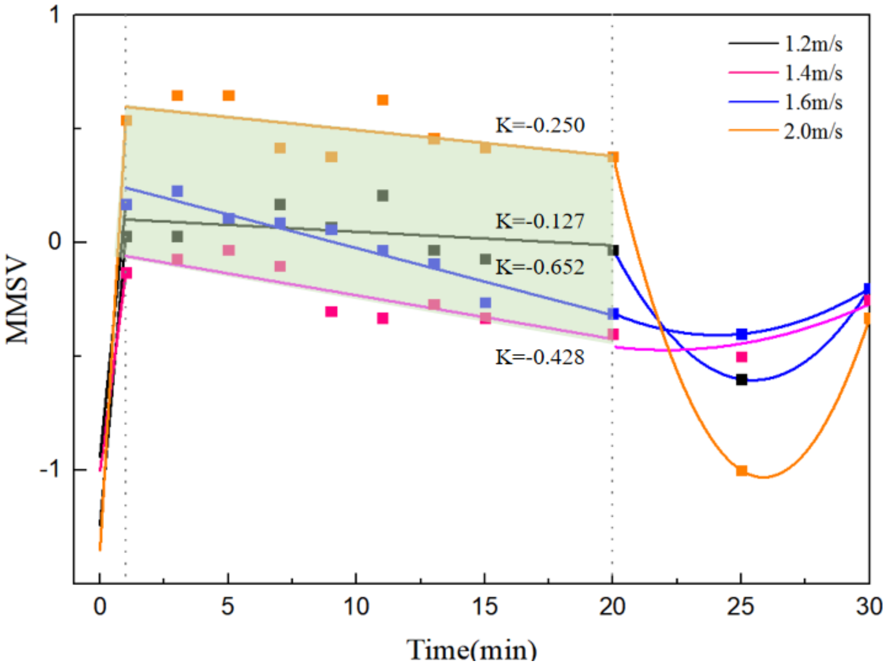


Fig. 7. The variation of MMSV (mean air movement sensation vote) with time.

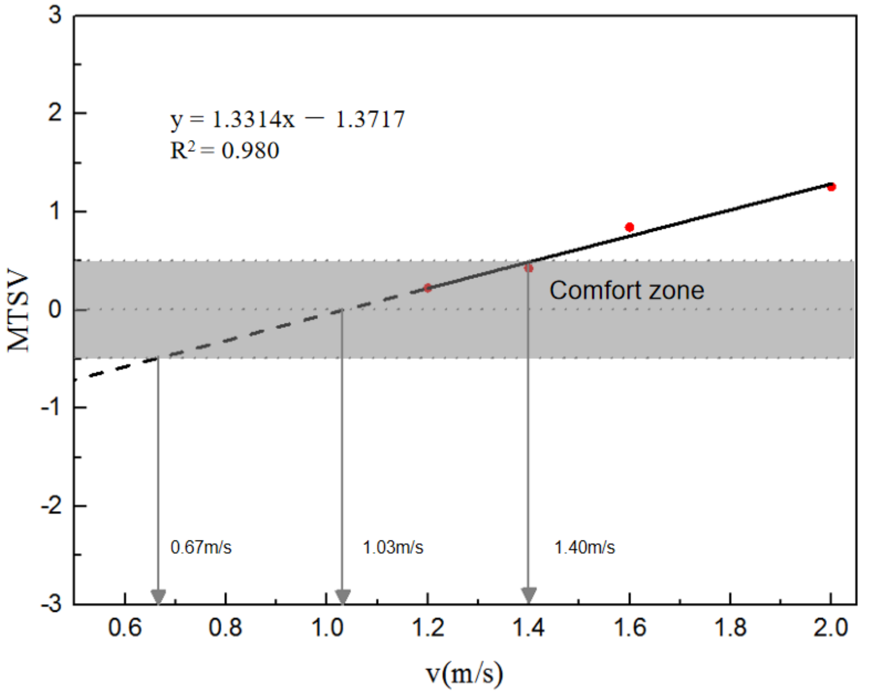
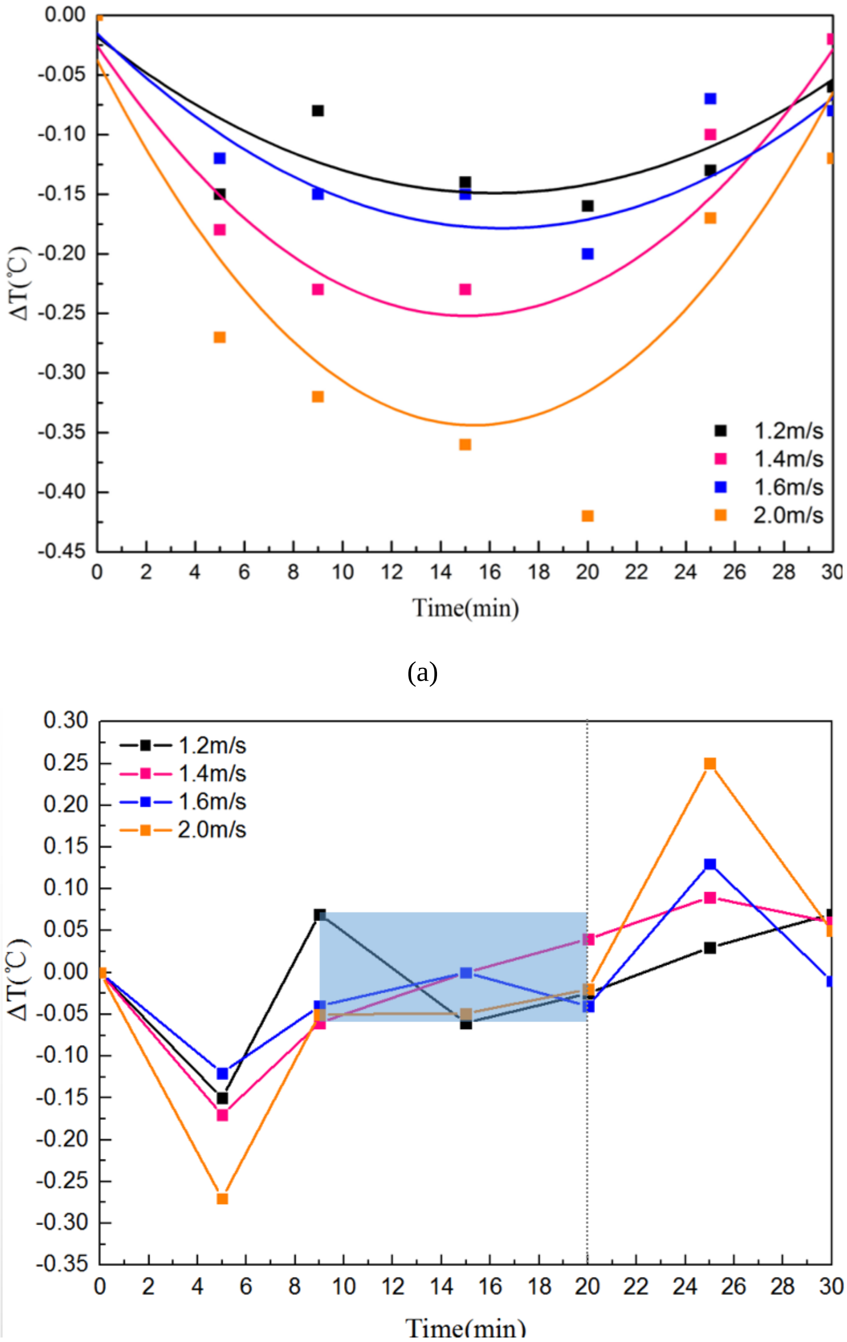


Fig. 8. Variation of MTSV (mean thermal sensation vote) against walking speed.



(a)

(b)

Fig. 9. The average changes of auditory canal temperature: (a) Compare with the initial value, (b) Compare with the last value.

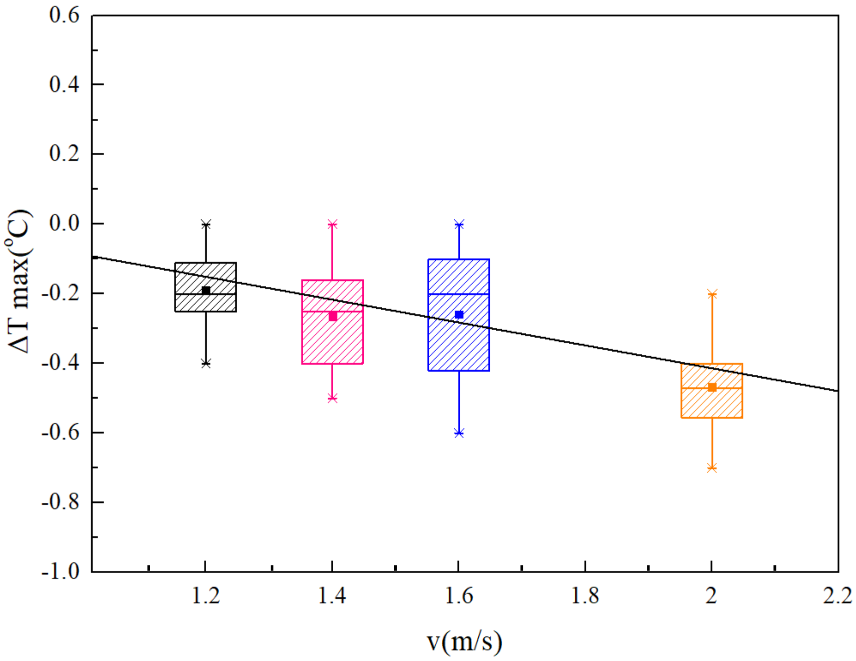
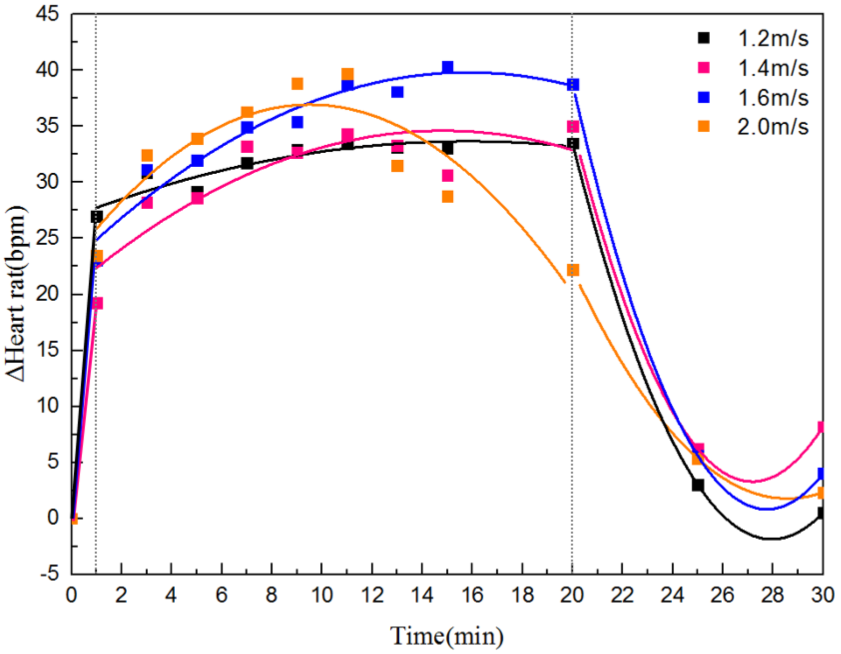
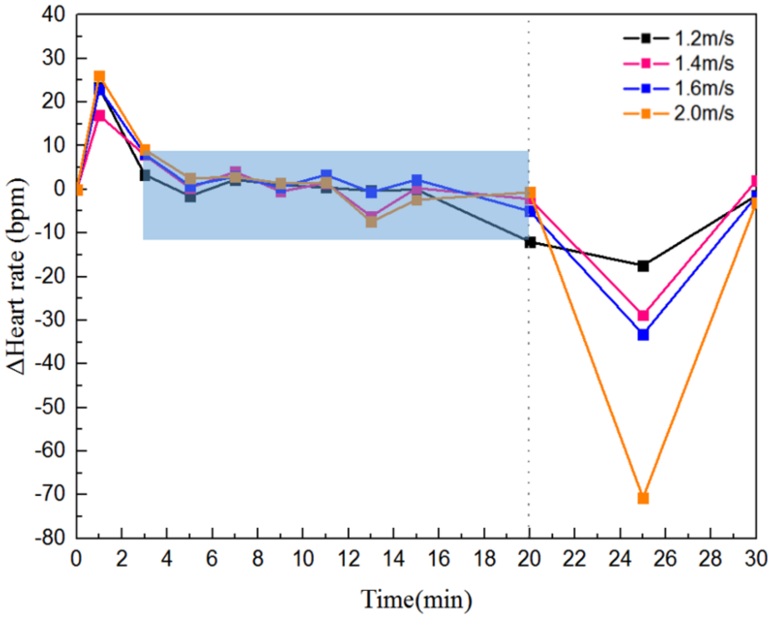


Fig. 10. The relationship between ΔT_{max} and *v*.



(a)



(b)

Fig. 11. The average changes of heart rate: (a) Compare with the initial value, (b) Compare with the last value.

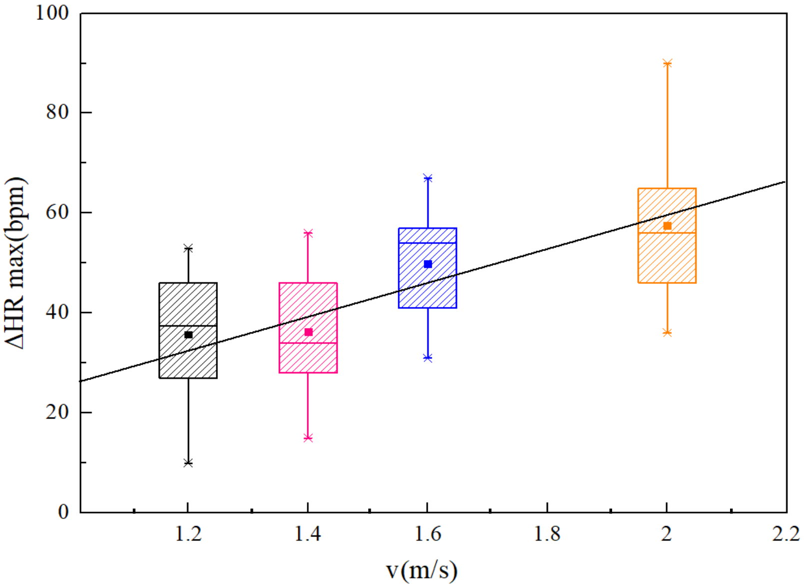


Fig. 12. The relationship between ΔHR_{max} and *v*.

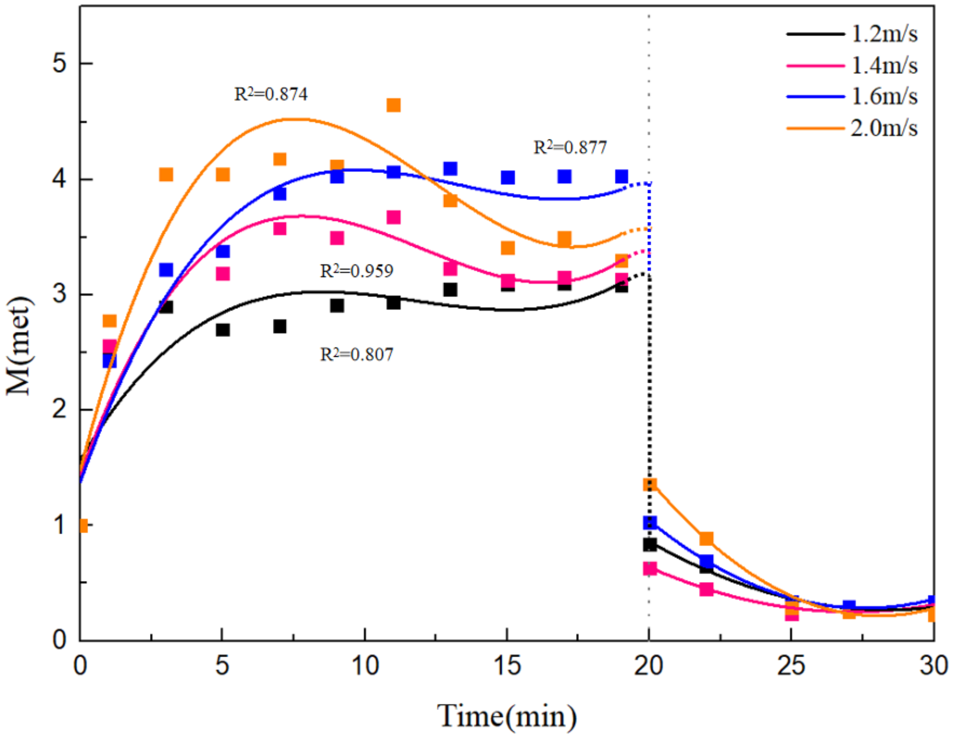


Fig. 13. The variation of average metabolic rate with time.

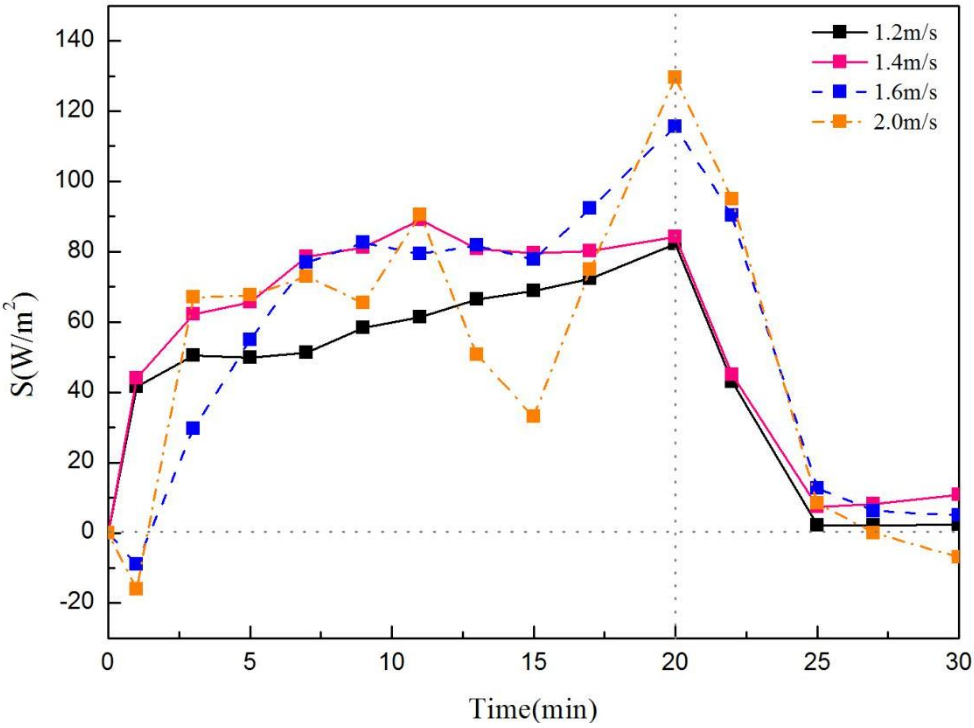
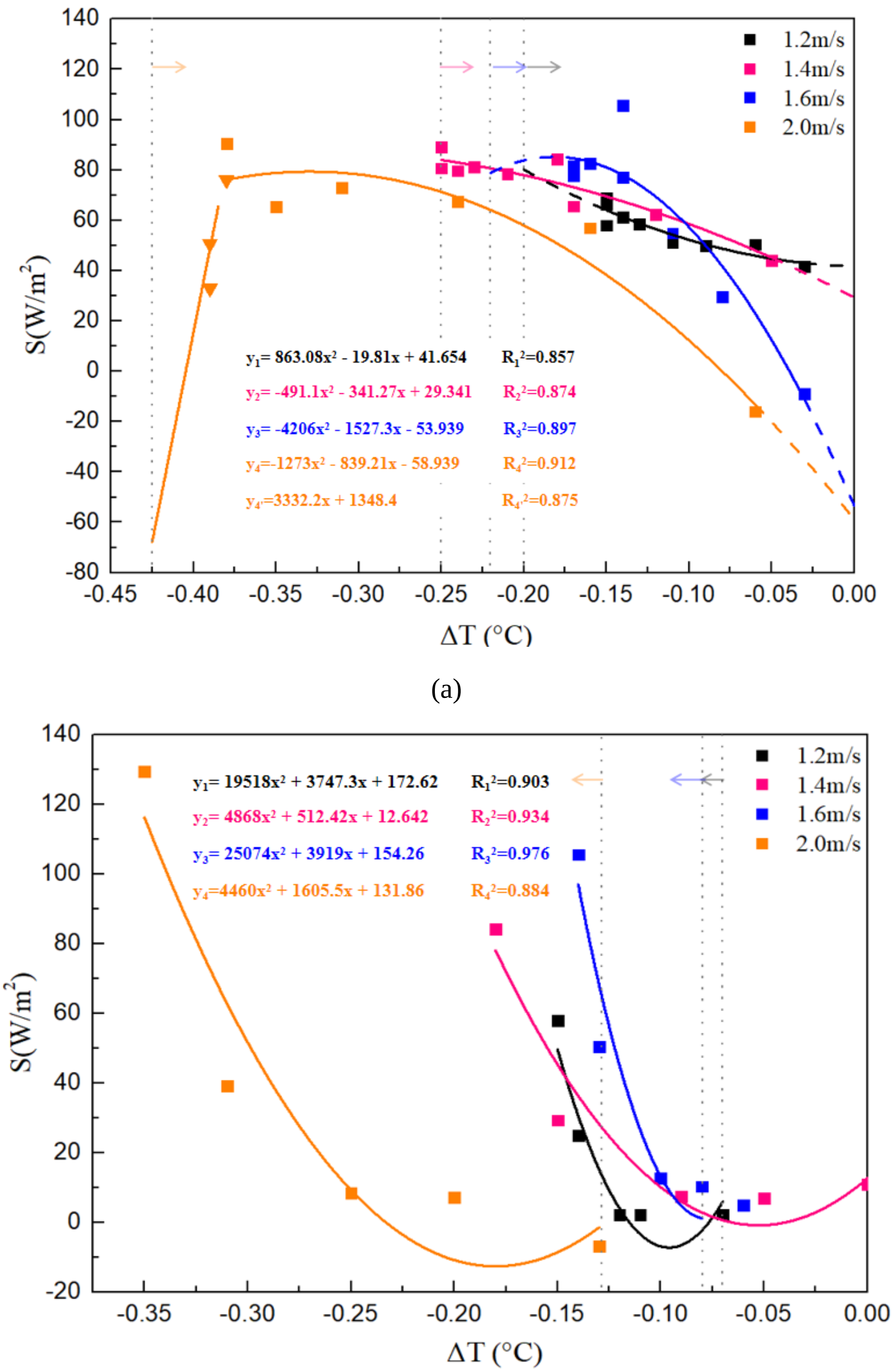


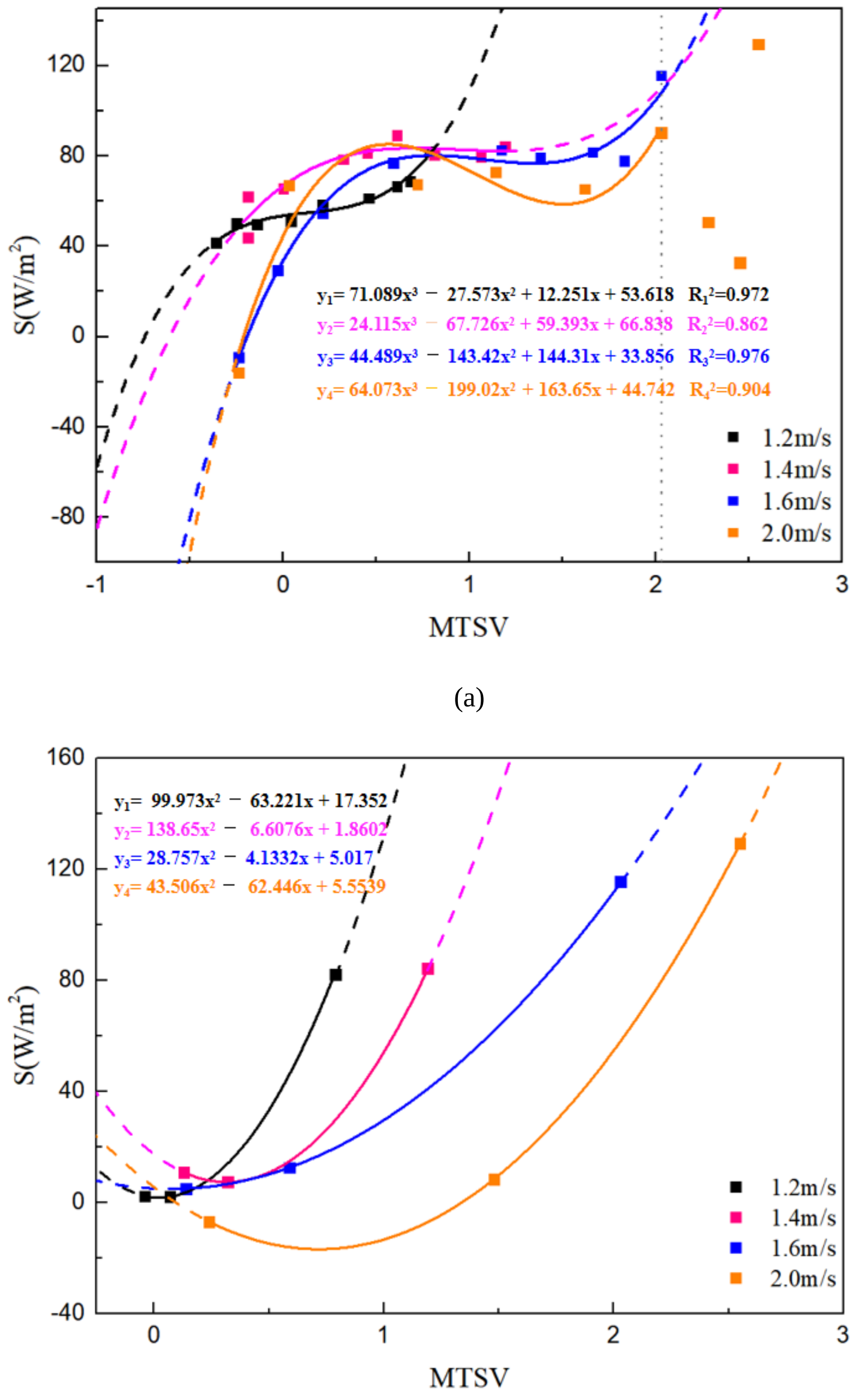
Fig. 14. The variation of heat storage with time.



(a)

(b)

Fig. 15. The relationship between ΔT and S (heat storage): (a) Exercising period, (b) Rest period.



(a)

(b)

Fig. 16. The relationship between MTSV (mean thermal sensation vote) and S (heat storage) : (a) Exercising period, (b) Rest period.

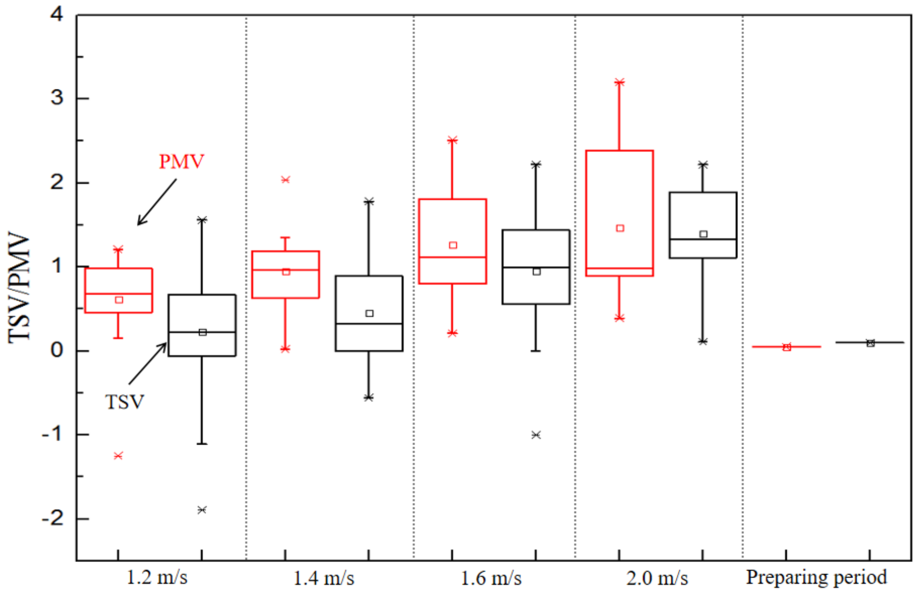


Fig. 17. The comparison between MTSV (mean thermal sensation vote) and PMV (predicted mean vote).

Declaration of Interest Statement

The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Highlights

- Metabolic activities of body movements remain key influential factor to thermal comfort.
- Experiments of walk speeds carried out for analyzing variations of air disturbance.
- The changes of thermal sensation and physiological indexes of human body were not synchronous.
- Based on regression model between thermal sensation and walking speed, the neutral walking speed were determined.