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Preferred temperature with standing and treadmill workstations

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ABSTRACT

Prolonged sedentary behavior has been shown to increase chronic diseases. Using standing and treadmill desk reduces sitting time, increases metabolic rate and thus has potential to improve health. There is little existing guidance on how to keep thermal comfort when using standing and treadmill desk. It is unknown what are the suitable ambient temperatures for occupants at elevated office activity levels. This experiment investigated thermal sensation and preferred temperature at elevated office activity levels, including sitting (SED), standing (STD), and two slow-walk speeds: walking at 1.2 km/h (TRD1) and walking at 2.4 km/h (TRD2). Comfort votes were obtained from 20 subjects under personal controlled ambient temperature. The active workstation significantly increased human metabolic level and reduced preferred temperature. The measured metabolic rates were 1.0, 1.1, 1.9 and 2.5 met for SED, STD, TRD 1 and TRD 2. The preferred ambient temperature reduced from 25.85 °C for SED, to 25.0, 24.1 and 23.2 °C for STD, TRD 1 and TRD 2 respectively. All subjects were comfortable at their preferred temperatures. PMV model was found to predict too cool temperature than needed for higher metabolic rates.

1. Introduction

Prolonged sedentary behavior, which is pervasive in contemporary occupational tasks, was confirmed to be significantly associated with an elevated risk of chronic diseases [1]. Since sedentary behavior was first highlighted as a risk factor to health in the 1950s [2], there have been extensive studies to determine the relationship between sitting time and health effect. Recent evidence showed that the extend periods of sitting affects health outcomes, even in individuals who are otherwise physically active. For example, several studies demonstrated that sitting time was associated with an elevated risk of all-cause and cardiovascular disease mortality, but was independent of other physical activity [3] [4]. More specially, increasing sitting time is strongly associated with rates of metabolic syndrome, type-2 diabetes mellitus, and obesity [4].

Office occupants were identified as a majority of current sedentary behavior that spent the day sitting. Therefore, workplace is a key setting to introduce strategies to reduce sitting time and increase break up periods to improve health [5] [6]. Recently, workstations wherein the user stands or walks using a specially designed "standing desk" or "treadmill desk" are getting more and more popular in modern office environment to replace traditional sedentary workstations. One main reason for many occupants to adopt standing and treadmill desks is the effectiveness of these workstations on increasing daily energy expenditure, and thus occupants could reduce their weight while improve health [7–9].

While standing and treadmill workstations are becoming popular, it is unknown if current thermal environments would satisfy occupants who are using those active workstations since metabolic rate would be higher. It is also unclear if current PMV-PPD based thermal comfort standards, such as ASHRAE 55 [10] and ISO 7730 [11] that are mainly applicable to sedentary activity, would be able to predict thermal comfort and provide reasonable design guidelines for spaces with active workstations. Metabolic rate (met) is the parameter which has been least studied among the six main variables of thermal comfort [12]. Due to the increased heat generated within the body with increased metabolic rate, a person's preferred neutral temperature should decrease to maintain the human body heat balance [13] [14]. McNall et al. [15] tested 420 human subjects (210 females and 210 males) dressed in 0.6 clo with three metabolic rate conditions (1.7, 2.2, 2.8 met) at temperatures from 12 to 26 °C, finding neutral temperatures of 22, 19 and 16 °C respectively.

The PMV model, developed by Fanger [16], was built based on three basic assumptions of conditions for thermal comfort. The first one is that human body must be in thermal balance, the second and third

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assumptions are that for a person in thermal comfort at a given activity level, his skin temperature and sweat secretion must remain in certain ranges. By reviewing historical data, Fanger constructed equations that predict comfortable skin temperature and evaporative heat loss from low activity levels. These equations were validated by Olesen et al. [17], who investigated human comfortable physiological state for different combinations of activity, clothing, temperature, humidity and air speeds. Finding that comfortable skin temperature and sweat rate are independent of environmental parameters and clothing levels, but they are depend on activity. Nielsen et al. [18] investigated 10 subjects dressed in shorts with different continuous and intermittent activities, found that the preferred temperature was 19 °C at 2.6 met and 18 °C at 5.0 met., and the skin temperatures and sweat rates preferred for comfort depend upon activity level. Similarly, McIntyre [19] also noted that comfort during exercise is achieved at an air temperature that produces a skin temperature below the sedentary level of about 34 °C but not low enough to suppress sweating. By comparing PMV prediction and field data, Humphreys and Nicol [20] pointed out that PMV predicts well when metabolic rate is lower than 1.4 met, beyond this large discrepancy would occur between PMV predictions and actual thermal sensation votes. A recently study by Wang et al. also found that the relation between comfortable skin temperature and metabolic rate for Chinese people in moderate activity did not agree well with Fanger's equation [21], suggesting Chinese people tended to have higher comfortable skin temperature than PMV prediction.

Preferred temperature method is a way to determine the comfortable temperature directly by allowing subjects to change the chamber temperature based on their preferences. Numerous studies using this method have been conducted to evaluate the validity of PMV model for different geographic locations [22] [23], different times of the day [24] [25], aged and gender [26–28]. It was found that PMV prediction matched preferred temperature well under sedentary activity, and there was no difference in terms of preferred temperature for different geographic locations, aged and gender, or times of the day. However, to date there is no study on preferred temperature at higher office activity levels. In the study by Nielsen et al. [18] on validating Fanger's comfort equations, they asked the exercising subjects every 10 min throughout the experiment whether he would prefer the environment to be warmer, cooler, or the same, and then altering the ambient temperature accordingly. Subjects in this study were professional athletes dressing only shorts while doing physical exercise rather than office activities. And their preferred temperature at each metabolic level were not sufficiently reported in the paper.

In order to provide comfortable environments for occupant with active workstations, we need to (1) quantify the metabolic rates for occupants with these new active workstations, and (2) understand their impact on thermal comfort. The objective of the study is to investigate human preferred temperature with active workstations and compare the results with PMV model predictions. The findings would shed lights in office environment design with active workstations.

2. Methods

The experiments were conducted in the climate-controlled chamber at Xi'an University of Architecture and Technology in December 2017. Outdoor temperature was around 0–10 °C.

2.1. Participants

Twenty subjects, all were university students (10 females and 10 males), participated in all four test conditions, which will be described later in Table 2. They were dressed in standard uniforms totaling 0.6 clo: long-sleeves cotton shirt, long pants, and the subjects' own underwear, sneaker and socks, as visible in Fig. 1. Before selecting the subjects, background surveys were performed to gather basic information such as height, weight, age, weekly exercise, tobacco use, and caffeine consumption. Only people in good health condition were recruited. Before conducting the experiment, the subjects' height and weight were measured on a medical height measurement instrument and a balance with a resolution of ± 2 g (PESA CB 2.2–100, PESA Ltd, Beijing, China). Their anthropometric data is summarized in Table 1. The study was approved by the Committee for the Protection of Human Subjects of Xi'an University of Architecture and Technology.

2.2. Facilities and measurements

Fig. 1a shows the experimental set-up in the climate chamber. Chamber A (measures 3.0 m × 2.4 m × 2.1 m) was used to simulate a typical office environment, it can control temperature to an accuracy of ± 0.2 °C, and RH ± 5%. Mean radiant temperature was controlled to be equal to air temperature, and air speed was less than 0.1 m/s. Air was supplied from the ceiling and returned from the lower side. The chamber can increase/decrease ambient temperature at 0.3–0.4 °C/min after a temperature setpoint change. The other chamber (Chamber B measures 4.5 m × 3.9 m × 2.7 m) was controlled at 26 °C and used as the pre-condition room and changing room.

Table 2 shows the test conditions. The temperature in the chamber A was controlled at 25.7 °C initially for the first 30 min, then the temperature was controlled by subjects for 60 min, under each of the four activity levels described below, in four separate tests. Relative humidity and air velocity were controlled at 50% and less than 0.1 m/s throughout the test. Four activity levels were tested, including sitting and typing (SED), standing and typing (STD), walking at 1.2 km/h and typing (TRD1), walking at 2.4 km/h and typing (TRD2). At SED condition, subjects seated in a plastic mesh chair that provided negligible additional insulation in front of a normal office desk (Fig. 1b). For STD condition, subjects stood for 1 h, with a height-adjustable desk (IKEA SKARSTA) (Fig. 1c). For TRD1 and TRD2 condition, subjects walked on a treadmill (LifeSpan TR1200B, LifeSpan Fitness/P. C. E. Inc. USA) with the speeds set at 1.2 km/h and 2.4 km/h, together with the same height-adjustable desk (Fig. 1d). During all tests subjects were asked to perform office activity (typing) through out the 1 hr test period.

The environmental parameters, including ambient temperature, air velocity, relative humidity, and globe temperature, were measured with the laboratory grade equipment according to ISO7726-1998 specification [29]. Air temperature and relative humidity (TD/TR-72ui datalogger, accuracy ± 0.25 °C, ± 2.5%) were measured at three heights (0.1 m, 0.6 m, and 1.1 m). Globe temperature (HQZY-1, TianJianhuayi Co., Ltd, Beijing, China, accuracy ± 0.3 °C), and air speed (WFWZY-1, TianJianhuayi Co., Ltd, Beijing, China, accuracy ± 0.05 m/s) were measured at 1.1 m height. The sample rates were 1 min for all physical measurements.

Physiological measurements Fig. 2 shows the equipment used for physiological responses in this study. Metabolic data were collected using the COSMED K5 wearable metabolic system (COSMED K5, COSMED S.r.l.,Italy) for each subject at the last 10 min in all tests (Fig. 2a). The K5 was calibrated on gas sensors, flowrate, and pressure before each testing. It uses a face mask that covered both the mouth and the nose to collect expired gas from the subjects, and the captured gas was analyzed in micro-dynamic mixing chamber provided oxygen consumption rate (VO_2), carbon dioxide output (VCO_2), ventilation (VE), and respiratory exchange ratio. The metabolic rate was then determined by measured VO_2, VCO_2, respiratory quotient (RQ), and A_{DU} according to equations (1)–(3) provided by ISO 8996 [31], as follows:

$$RQ = VCO_2 / VO_2 \tag{1}$$

$$EE = (0.23RQ + 0.77) * 5.88 \tag{2}$$

$$M = EE * VO_2 / A_{Du} \tag{3}$$

Where:

a. Chamber set-up b. Sitting and typing c. Standing and typing d. Walking and typing

Fig. 1. Experimental set-up.

Table 1
Subjects' anthropometric information.

	Sample size	Age	Height (cm)	Weight (kg)	BMI*(kg/m^2)	A_{Du}**(m^2)
Women	10	24.0 ± 1.6$^\#$	163.4 ± 5.3	58.3 ± 9.2	21.8 ± 2.4	1.79 ± 0.12
Men	10	22.9 ± 2.0	171.7 ± 5.4	67.8 ± 7.7	22.9 ± 1.7	1.65 ± 0.14
all	20	23.5 ± 1.8	167.6 ± 6.7	63.1 ± 9.6	22.3 ± 2.1	1.72 ± 0.15

*Body Mass Index (BMI) = Mass (kg)/Height (m)^2;
$^\#$Standard deviation;
$^{**}A_{Du} = 0.202 \times (\text{weight})^{0.425} \times (\text{height})^{0.725}$.

Table 2
Test conditions.

Time (min)	Temperature (°C)	Relative humidity (%)	Air velocity (m/s)	Clothing (clo)	Activity
0–30	25.7	50	< 0.1	0.6	Sedentary
30–90	Controlled by subjects	50	< 0.1	0.6	Sitting and typing (SED) Standing and typing (STD) Walking at 1.2 km/h and typing (TRD1) Walking at 2.4 km/h and typing (TRD2)

RQ is the respiratory quotient;
EE is the energetic equivalent (W h/l O_2);
M is the metabolic rate (W/m^2);
A_{Du} is the body surface area, in square meters (m^2), given by the Du Bois formula.

Skin temperature was measured on forearm, chest, thigh and shin using small wireless temperature sensors (PyroButton-L, Opulus Ltd, PA, USA) every 10 s continuously (Fig. 2e). Mean skin temperature (T_{sk}) was calculated as an area-weighted average of measurements using the following equation (4), adapted from NL Ramanthan [30].

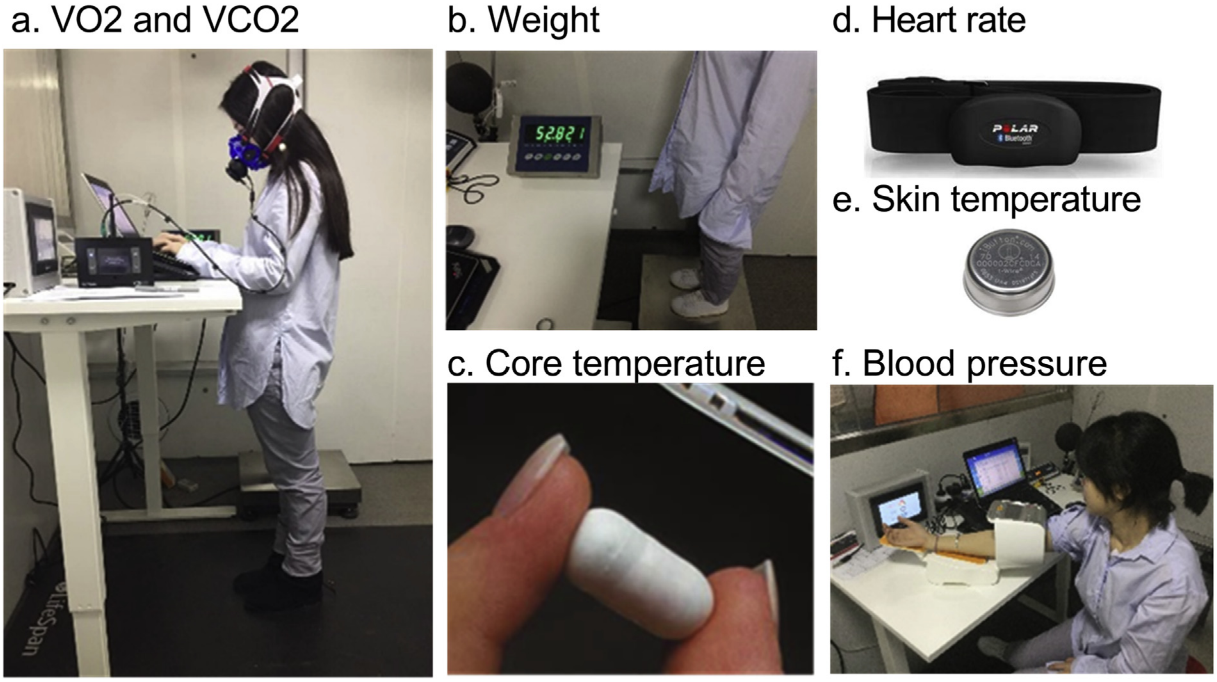
$$T_{sk} = 0.3 *T_{arm} + 0.3 *T_{chest} + 0.2 *T_{thigh} + 0.2 *T_{shin} \tag{4}$$

Weight loss was measured on a balance (Fig. 2b) with a resolution of ± 2 g (PESA CB 2.2–100, PESA Ltd, Beijing, China). Evaporative heat loss was calculated from the weight loss of last 10 min in the test assuming subjects thermal condition reach equilibrium. Latent respiration heat loss was subtracted from the total heat loss based on Fanger's equation [16]. Skin wettedness was calculated from actual evaporative heat loss and maximum evaporative heat loss for each condition.

Core temperature (T_{cr}) measurements were made on four male subjects using telemetry pills (accuracy ± 0.1 °C; CorTemp®, HQ Inc, Florida, USA) in four tests (Fig. 2c), for four metabolic levels. Pills were ingested 2 h before testing with warm water of 36.7 °C. T_{cr} data were sampled every 10 s using a telemetry receiver (CorTemp®, HQ Inc, Florida, USA) attached on the back of waist of the subjects.

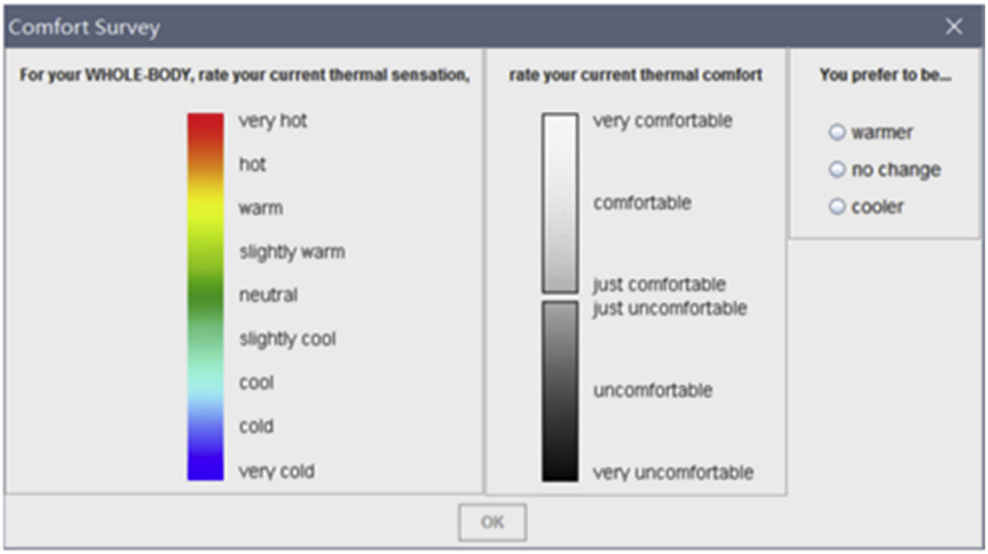
Heart rate was continuously monitored (every 10 s) on each subject using a Polar heart rate sensor (Polar H10, Polar Electro Oy, Kempele, Finland) (Fig. 2d). Blood pressure was measured periodically on Omron blood pressure monitor HEM-1020 (accuracy ± 3 mmHg, ± 2.5%) and expressed in mmHg (Fig. 2f).

Questionnaire survey. Comfort questionnaires repeatedly appear on a computer based on designed time intervals, to obtain instantaneous thermal sensation, thermal preference and other subjective comfort responses. Subjects rated their thermal sensation (TS), thermal acceptability (TA), thermal comfort (TC) responses on continuous scales. The TS scale units are: −4 very cold, −3 cold, −2 cool, −1 slightly cool, 0 neutral, 1 slightly warm, 2 warm, 3 hot, 4 very hot. TA (and TC) were measured on a nine-point scale with a break, in which the positive values (0.01 'just acceptable' ('comfortable') to 4 'clearly acceptable' ('very comfortable') represent satisfaction and the negative values (−0.01 'just unacceptable' to −4 'clearly unacceptable') represent dissatisfied. Three-point scales are used for thermal preference (TP) (−1 want cooler, 0 no change, 1 want warmer). In addition to the regular thermal comfort questionnaire, the subjects were asked after each exercise level to vote their perceived physical exertion on Borg



a. VO2 and VCO2 b. Weight c. Core temperature d. Heart rate e. Skin temperature f. Blood pressure

Fig. 2. Physiological measurements. a) VO2 and VCO2, b) weight, c) core temperature, d) heart rate, e) skin temperature, and f) blood pressure.



Comfort Survey

For your WHOLE-BODY, rate your current thermal sensation,

very hot
hot
warm
slightly warm
neutral
slightly cool
cool
cold
very cold

rate your current thermal comfort

very comfortable
comfortable
just comfortable
just uncomfortable
uncomfortable
very uncomfortable

You prefer to be...

○ warmer
○ no change
○ cooler

Fig. 3. Sample survey rating scales (senstaion, comfort, preference) used in the experiment.

Rating of Perceived Exertion (RPE) Scale [32] (6 – No exertion at all; 7 – Extremely light; 9 – Very light; 11 – Light; 13 – Somewhat hard; 15 – Hard; 17 – Very hard; 19 – Extremely hard; 20 – Maximal exertion). Sample voting scales are shown in Fig. 3.

2.3. Experimental protocol

Each subjects participated in four 90 min experiment between the hours 10:00 a.m. and 6:30 p.m., typical working hours in China. Scheduling was random. Fig. 4 shows the test procedure used in this study. Subjects were asked to refrain from moderate to vigorous physical activity the day before the test, as well as alcohol and caffeine-containing drinks. The subjects were asked to arrive 30 min before the test to avoid entering the chamber with an elevated metabolic rate. For the four subjects with core temperature measurements, they were asked to arrive at the chamber 2 hr before the experiment and ingested the sensor pill with warm water same as body core temperature, 36.7 °C. When subjects arrived at the lab, they changed into test clothing and secured temperature and HR sensors to their skin in chamber B, which was controlled at 25.7 °C throughout. Then they entered the test chamber A, which was controlled at 25.7 °C initially, the neutral temperature as predicted by PMV model for sedentary activity (1.0 met). After 30 min adaptation period, weight and blood pressure were measured. Then the subjects started to perform different office tasks (SED, STD, TRD1, and TRD2) according to the experimental schedule for 60 min, during which they could adjust room setpoint temperature on a touch screen controller showing “warmer”, “no change” and “cooler” at any time they want. One-hit on warmer/cooler button would increase/decrease the setpoint temperature by 0.5 °C, which took about 1-2 min for the chamber to response. After 50 min test they were weighted again and were asked to wear K5 for metabolic rate measurement for 10 min. The subjects wore the face mask and performed the same task as in the

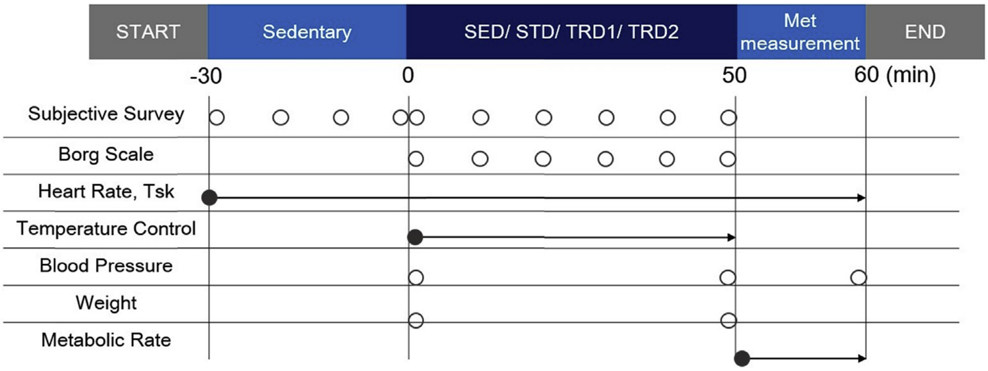


Fig. 4. Experimental procedure, open circles indicate time to fill out the questionnaire or to measure physiological response, and the dot and arrow means continuous measurement).

previous 50 min. Blood pressure and weight were measured again after metabolic rate measurement was completed. Survey showed up on the computer screen every 10 min, included TS, TA, TC, TP, and local TS were asked every 10 min throughout the test. For the STD, TRD1, and TRD2, the height-adjustable desk was adjusted before the tests by the investigator to ensure a comfortable height for the subjects.

2.4. *Statistical methods*

Statistical analysis was performed using Graphpad Prism 6 for Windows (GraphPad Software, San Diego, California US). The experiment was treated as a repeated measures design. The independent variables are activity levels (SED, STD, TRD1, and TRD2) and time. Dependent variables are preferred air temperature, subjective and physiological response. Data were tested on normality using Shapiro–Wilk test, One-way repeated measures analysis of variance (ANOVA) test was used for normally distributed data, while Friedman's test was used for non-normally distributed data. Significance was accepted at 0.05.

3. Results

3.1. *Measured metabolic rate*

Measured metabolic rate for each activity is shown in Fig. 5. The effect of test condition was significant (F (2.594, 49.28) = 2.34, $R^2 = 0.06$). Post-hoc analysis using *t*-test shows that both TRD1 (1.9 ± 0.3 met) and TRD2 (2.5 ± 0.3 met) significantly increased metabolic rate compared to control condition (SED 1.0 ± 0.2 met, $P < 0.001$), but the difference between SED and STD (1.1 ± 0.2 met) ($P = 0.27$) was small and not significant. Met was higher at TRD2 in comparison to TRD1 ($P < 0.001$), and increased significantly from 1.9 to 2.5 met. Met was higher at TRD1 in comparison to STD ($P < 0.001$), and increased significantly from 1.1 ± 0.2 to 1.9 ± 0.3 met.

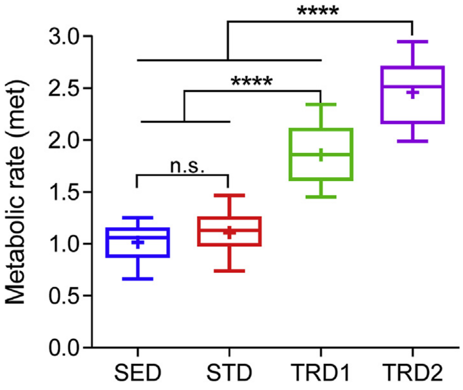


Fig. 5. Metabolic rate at each test condition. **** = significant difference ($P < 0.0001$). n.s. = no significant difference.

3.2. *Preferred temperature*

Fig. 6a shows the mean preferred temperatures for each activity over time. Preferred ambient temperature reached stable within 18 min for SED and STD. For TRD1 (1.9 met), 48 min into the test, the preferred ambient temperature reached stable. For the TRD2 (2.5 met), it was after 55 min that the preferred ambient temperature reached stable.

Fig. 6b shows the steady state preferred ambient temperature at each condition. The preferred temperature for each subject was the temperature setpoint that the subject set at the end of each experiment. Activity levels have significant effects on the preferred ambient temperature ($p < 0.001$). The preferred temperatures were significantly different from each other under all test conditions (post-hoc *t*-test, $P < 0.05$). At SED, the preferred ambient temperature was 25.9 ± 0.9 °C. Preferred temperature at STD (25.0 ± 1.0 °C) decreased over SED by 0.9 °C, at TRD1 (24.1 ± 1.5 °C) by 1.8 °C, and at TRD2 (23.2 ± 1.1 °C) by 2.7 °C.

3.3. *Physiological responses*

Fig. 7a presents the average mean skin temperature for all test subjects at each test condition. After 30 min adaptation period, the mean skin temperature at each condition was approximated around 33.5 °C, no significant differences were observed among test conditions. Skin temperature remained stable for SED throughout the test. It took around 45 min for skin temperature to stabilize for STD, TRD1, and TRD2. As shown in Fig. 6b, stabilized mean skin temperature at SED, STD, TRD1 and TRD2 were 33.4 ± 0.5 °C, 32.8 ± 0.6 °C, 32.9 ± 0.7 °C and 32.6 ± 0.6 °C, respectively. Significant differences were only found for STD, TRD1and TRD2, compared to SED ($p < 0.001$). No significant difference was found between STD, TRD1, and TDR2.

Core temperature for each condition was tested on four male subjects under 4 metabolic levels, the average values over time are show in Fig. 8a. Core temperature remained stable for all test conditions. As shown in Fig. 8b, the core temperatures at SED, STD, TRD1 and TRD2 were 37.3 ± 0.3 °C, 37.3 ± 0.1 °C, 37.4 ± 0.3 °C, and 37.4 ± 0.2 °C. There were no significant differences between all test conditions.

Evaporative heat loss was significantly affect by activity levels ($P < 0.001$, Fig. 9). A greater evaporative heat loss was observed at TRD1 (18.2 ± 11.6 W/m^2) and TRD2 (27.6 ± 16.4 W/m^2) over SED (10.3 ± 6.4 W/m^2) and STD (9.9 ± 3.5 W/m^2), but no difference was seen between SED and STD. The same was found for skin wettedness. Skin wetteness was 0.07 ± 0.04 at SED and 0.07 ± 0.02 at STD, and walking significantly increased skin wettedness to 0.13 ± 0.07 at

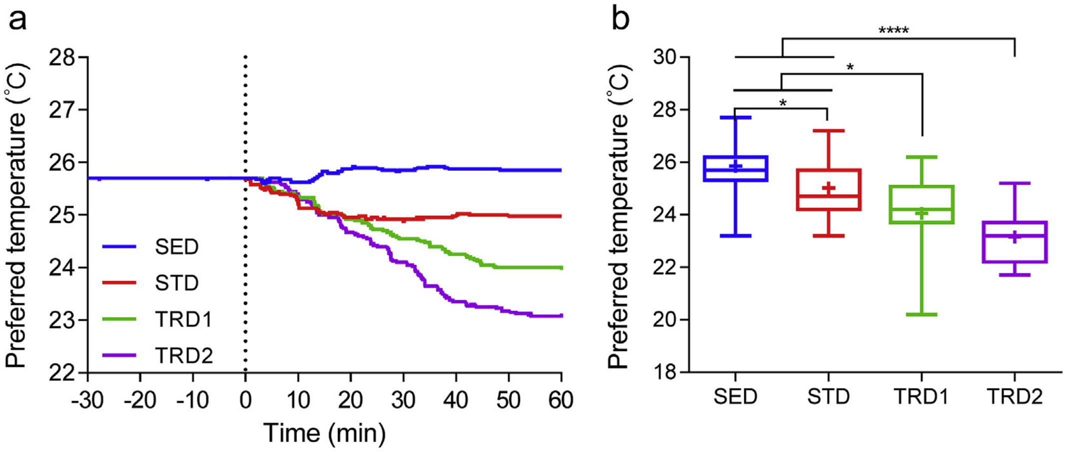


Fig. 6. Mean preferred temperatures a) over time, and b) steady state at each test condition. ****P < 0.0001. *P < 0.05.

TRD1 and 0.18 ± 0.11 at TRD2 (P < 0.05).

A statistically significant elevation of heart rate was observed during the STD (90 ± 9 bpm), TRD1 (93 ± 9 bpm) and TRD2 (93 ± 9 bpm) conditions compared with SED ((77 ± 8 bpm, P < 0.001), but no significantly differences were observed between STD, TRD1 and TRD2.

Standing systolic blood pressure increased to 102 ± 14 mmHg from 97 ± 12 mmHg during sitting (Fig. 10). It increased to 103 ± 10 mmHg at TRD1 and 107 ± 15 mmHg at TRD2, but no difference was significant between all conditions. As for diastolic blood pressure, at sedentary it was 58 ± 9 mmHg, at STD, 64 ± 7 mmHg, at TRD1, 67 ± 9 mmHg, and at TRD2, 64 ± 9 mmHg. Similarly, there were no significantly differences between all conditions.

3.4. Subjective responses

Fig. 11a shows the mean thermal sensation votes for the four activity levels over the 90 min test, and the bottom figure shows the mean thermal sensation (TS) votes of all subjects for each test condition at the end of the 90 min test. After the 30 min adaptation period in neutral temperature, the thermal sensation of all subjects reached close to 0.5, between neutral and slightly warm (time 0 in Fig. 11a). No significant difference was observed through the following 60 min test procedure and steady-state TS (Fig. 11d) since subjects could adjust temperature per their preferences.

Fig. 11b shows the thermal comfort (TC) votes at each test condition, scale ranging from “Very uncomfortable” (−4) to “Very comfortable” (4). Fig. 11c shows the thermal acceptability (TA) votes for the different conditions. The top figures show that the TC and TA votes increased when subjects began to control the ambient temperature, indicating the subjects were able to improve their human thermal comfort when they could control ambient temperature by themselves. The bottom figures (Fig. 11e and f) show the average votes at the end of the 90 min tests, and no significant differences were found among the four test conditions.

Fig. 12a shows the percentage of votes regarding thermal preference (TP) for all test conditions. Subjects generally preferred “no change” at SED. At STD, the 10% preferring cooler temperatures. At TRD1, the 15% preferring cooler. At TRD2, 20% subjects preferred to be cooler.

Fig. 12b shows a large variation in perceived exertion on the Borg scale. Overall, the study's range of metabolic conditions produced significant differences in perceived exertion at each activity level. Subjects' median perceived exertion were respectively 8, 10, 10, 12 at SED, STD, TRD1 and TRD2 conditions, corresponding to “very light”, “light” and “hard” exertion on the Borg scale. A statistically significant elevation was observed during the STD, TRD1 and TRD2 conditions compared with SED (P < 0.001), but no significantly difference were observed between STD, TRD1 and TRD2. The higher the activity level, the greater the variation among individuals is.

4. Discussion

To our knowledge, this study is the first to explore the preferred temperature for comfort in elevated office activity levels using standing and treadmill workstations. Results show that standing only increased the seated metabolic level slightly, but treadmill workstation

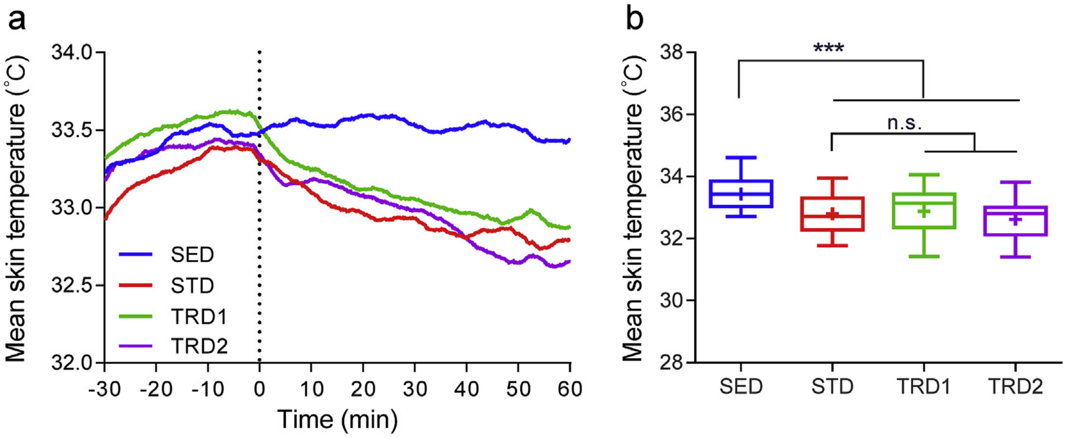


Fig. 7. Mean skin temperatures a) over time, and b) steady state at each test condition. ***P < 0.001. n.s. = no significant difference.

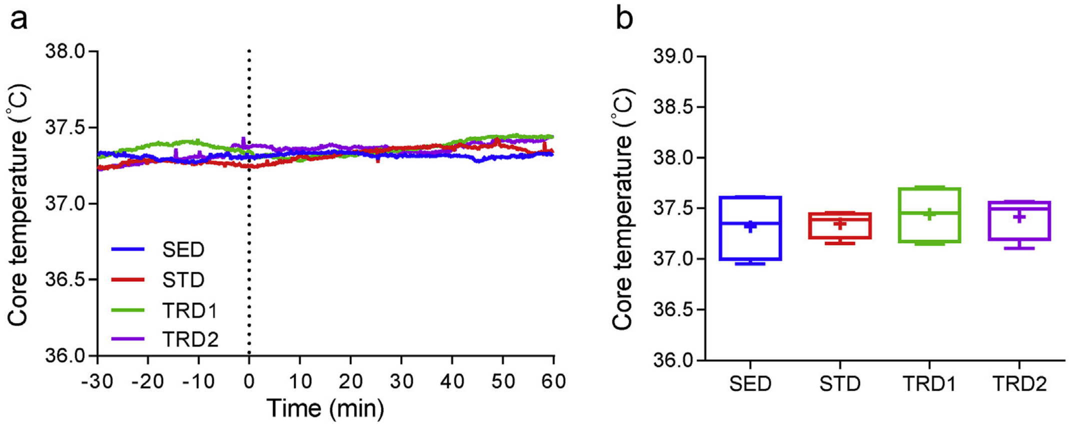


Fig. 8. Core temperatures a) over time, and b) at steady state for each test condition.

significantly increased human metabolic level. The preferred ambient temperature decreased 0.9 K each time as activity changed from SED to STD, TRD1, and to TRD2, while human thermal comfort was well maintained at these subjectively preferred temperatures. Preferred mean skin temperatures were only found to be significantly different between active workstations and sedentary, but not among the active workstations. Evaporative heat loss was significantly higher at TRD1 and TRD2 than STD and SED. Core temperature remained same for all test conditions, and HR was significantly elevated for active workstations. This experiment lends further support using active workstations as a means of increasing physical activity, which might improve health in work environment.

This study explored metabolic rate of simulated office activities by measuring the metabolic rate of typical occupational tasks in sitting, standing and walking. The measured metabolic rate for sedentary (1.0 met) and standing (1.1 met) are not significantly different from the metabolic rate defined in ISO 8996 (seat activity, office - 1.2 met) [29], 7730 (seat activity, office −1.2 met; standing, relaxed - 1.2 met) [11] and ASHRAE 55 [10] (Seated, typing - 1.1 met; Standing, relaxed - 1.2 met), although our measured values are a little lower. This is in agreement with other studies who also found that there was no significant difference between sitting and standing using indirect calorimetry [33–36], which actually suggesting that for physical activity under 1.5 MET, standing shall be defined as sedentary activity. We found that walking on a treadmill would significantly increase metabolic rate, this is in line with previous findings, suggesting that comparing to standing workstation, treadmill workstation would have more profound effect in increasing physical activity in workplaces [37].

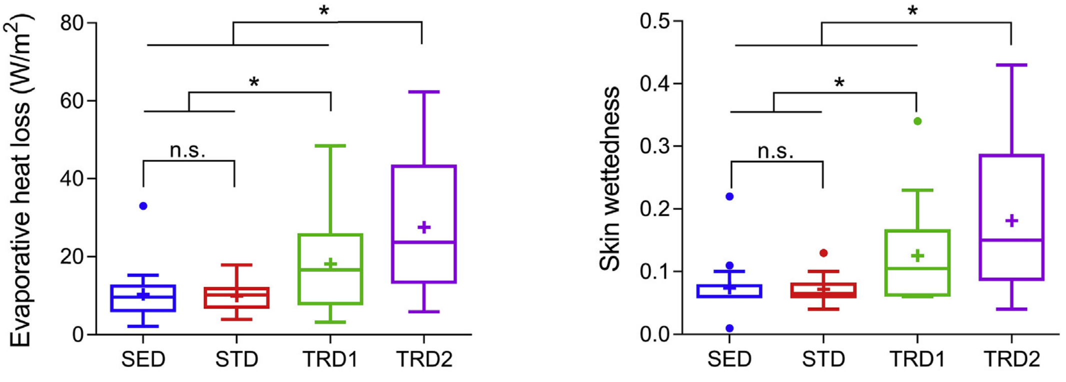
The relation between the preferred temperature and metabolic rate is shown at Fig. 13 and compared with neutral temperatures predicated by PMV. Regression analysis of data shows that the preferred temperature decreases as metabolic rate increases ($R^2 = 0.95$, $P < 0.05$).

$$T_{prefer} = -1.668 * met + 27.2\ (^{\circ}C) \tag{5}$$

The preferred temperatures at sedentary and standing activity were 25.9 and 25.0 °C in our study. This is almost identical to the neutral temperature predicted by PMV (25.7 and 24.8 °C). However, at higher activity levels, large discrepancy was found (Fig. 14). At 1.9 and 2.5 met, the differences between PMV and our study were 4.8 and 8.1 K (Fig. 14) respectively. PMV model tends to predict much cooler environments at higher metabolic rate than the measured data.

McNall et al. [15] investigated 420 subjects' (210 males and 210 females) thermally neutral temperature at 1.7, 2.2 and 2.8 met, and found that the thermally neutral temperature was 22, 19 and 16 °C respectively. His findings are also plotted on Fig. 14. It is evident that the neutral temperature found by McNall et al. is closer to PMV prediction. However, it is understandable since Fanger used McNall et al. experimental data for the construction of PMV model, who found that comfortable levels of skin temperature and sweat rate were affected by activity levels. More analysis explaining these differences are further provided below.

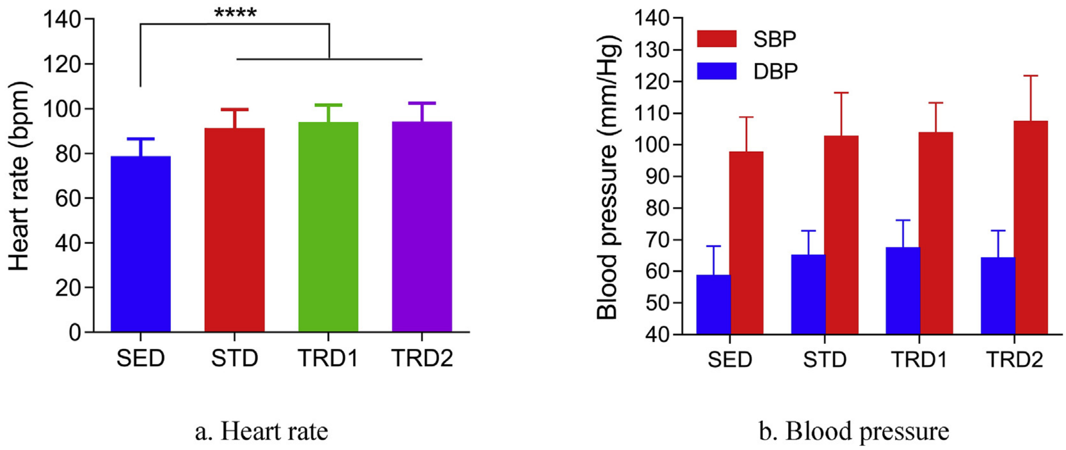
Fig. 14a shows the relation between mean skin temperature, evaporative heat loss against activity level for the current study and standard PMV-PPD model, studies of Gonzalez [14] and Wang et al. [21]. There is a trend that the mean skin temperature decreases with increasing activity. The tendency from our study is close to the studies of Gonzalez and Wang et al., both gave the linear equations to calculate neutral skin temperature at different activity levels, and there was very



a. Evaporative heat loss

b. Skin wettedness

Fig. 9. Evaporative heat loss (a) and Skin wettedness (b) at each condition. *$P < 0.05$.



a. Heart rate

b. Blood pressure

Fig. 10. Heart rate (a) and Blood pressure (b) at each condition. ****P < 0.0001.

small difference among these three relations. The mean skin temperature predicted by PMV model is more sensitive to metabolic rate than our measured value. At lower metabolic rate levels, the preferred skin temperature in our study is similar to the PMV equation. For example, at sedentary (1.0 met), the preferred skin temperature was at 33.4 °C identical to 33.5 °C predicted by PMV. However, at 1.1 met, 1.9 met, and 2.5 met, the preferred skin temperatures from our study were significantly higher than the PMV predictions. The linear regression of metabolic rate and comfortable skin temperature in our study was not significant ($P = 0.29$), indicating that for the measured activity levels (1.0–2.5 met), there was no clear relation between metabolic rate and comfortable skin temperature.

Fig. 14b shows the relation between evaporative heat loss and activity level for people in thermal comfort. Good linear correlation was found between metabolic rate and between evaporative heat losses ($P < 0.05$, $R^2 = 0.93$). The comfortable evaporative heat loss increases as metabolic rate increases. The trend is the same as PMV equation but the magnitude is smaller, especially in higher metabolic levels. Nieslen et al. [18] found that at high activities (4.3 met), subjects preferred the environment that increased their sweat rate rather than the environment that decreased their skin temperature. Our results indicated that the same is true for 1.9–2.5 met, at which our subjects preferred similar skin temperature but higher evaporative heat loss as metabolic rate increased.

Several possible reasons could contribute for the differences between PMV and current findings in terms of preferred temperature, comfortable skin temperature and evaporative heat loss. Firstly, our study investigated continuously office work, while Fanger's equation was derived from the study by McNall et al. [15] that was with intermittent work (periodical standing and stepping), and it was found in exercise physiology studies that intermittent exercise would affect human thermoregulation and physiological responses in terms of heat storage, skin and core temperature, and evaporative heat loss [38] [39], so as their subjective responses. Secondly, our subjects were doing

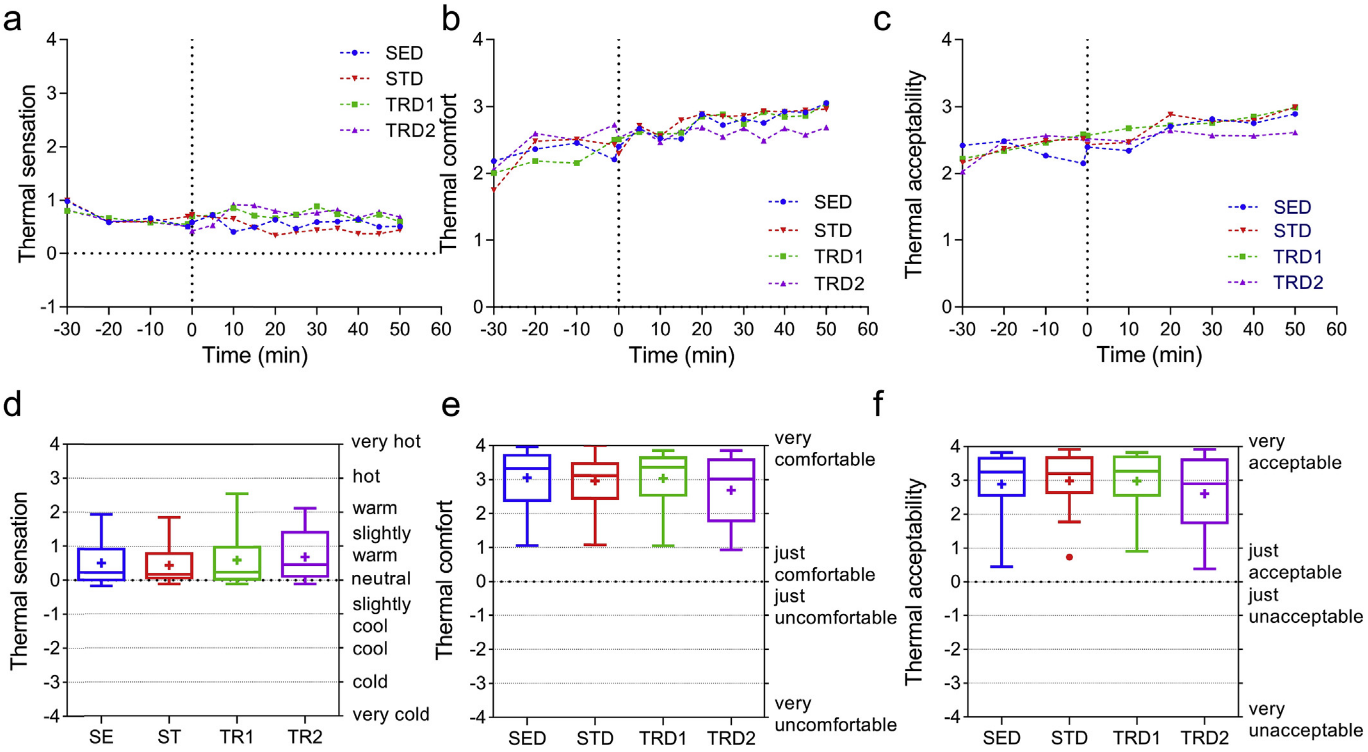
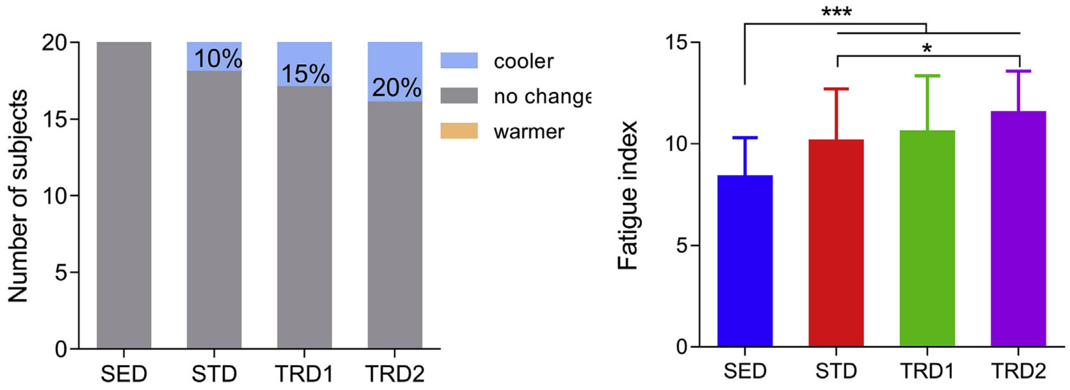


Fig. 11. Mean TS (a) TC (b) and TA (c) over time, and steady-state TS (d), TCf).



a. Thermal preference.

b. Perceived exertion on Borg scale

Fig. 12. Thermal preference (a) and Perceived exertion (b).

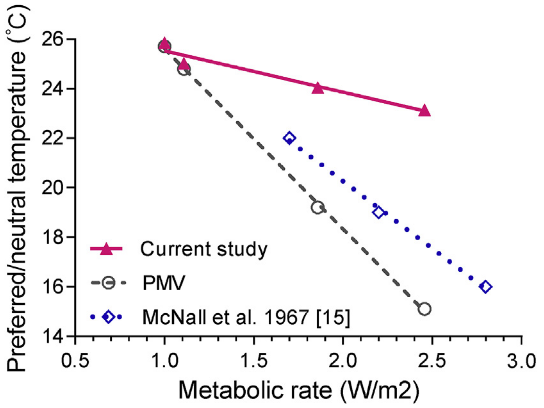
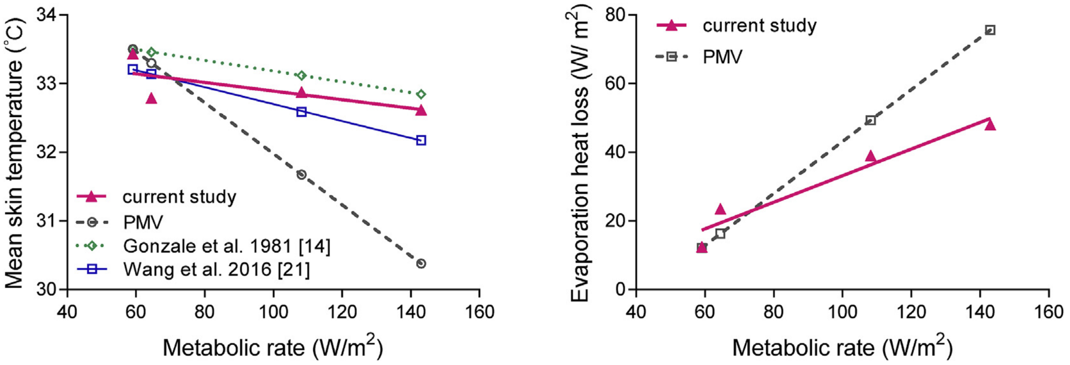


Fig. 13. The relation between metabolic rate and preferred temperature.

office work (typing) during the experiments, their preference on skin temperature may be different from subjects who were doing physical exercise in the other studies. Thirdly, in this study, we use the preferred temperature method rather than exposing subjects to different fixed temperatures. The difference in experimental method may contribute to the difference in the preferred skin temperature found in the current study. Fourthly, our study was conducted in winter season, thus a preference for slightly warmer temperature rather than neutral was found, as suggested by McIntyre [19]. This would also affect human subjective and physiological responses. However, season itself could not explain all the differences since the study by McNall et al. [15] and Nielson et al. [18] were also conducted in winter (November). Therefore, ethical background (Chinese vs. Americans vs. Danish) may also affect the results and need to be studied in the future.

Occupants employing active workstations may need lower room temperatures to feel comfortable, and decreasing the setpoint of thermostat will significantly increase the energy use for cooling [40]. However, reducing room temperatures may affect thermal comfort of occupants that are using normal sedentary workstations since the temperature would be too cool for them. Actually, even for the same activity level, there were large inter-individual differences in measured metabolic rate (Fig. 5), preferred ambient temperature (Fig. 6b), preferred skin temperature (Fig. 7a) and preferred sweat rate (Fig. 9b), especially at higher activity levels with active workstations. For spaces with different types of workstations, it is hard to satisfy every occupant with one single temperature setpoint under such circumstance. In this case, conditioning system that could tackle individual differences in thermal comfort requirements, such as personal comfort systems (PCS) shall be introduced in such spaces to satisfy personalized thermal comfort requirements [41] and save energy at the same time [40].

Also, in the current study, the preferred temperatures were achieved by allowing subjects to control the ambient temperature. The preferred air temperatures indicate ideal conditions for the tested metabolic levels, but they do not necessary prove that people with active workstations would not accept the ambient temperature which is set for sedentary people (eg. 26 °C for summer). In the current study, the preferred ambient temperature for the standing subjects is 0.9 K lower



a. Mean skin temperature and activity level for people in thermal comfort.

b. Evaporative heat loss and activity level for people in thermal comfort.

Fig. 14. Comparisons with PMV model.

than the preferred temperature for sedentary people, which results in 0.3 scale warmer thermal sensation. Comfort is defined within ± 0.5 thermal sensation scale in Standards. Therefore, for standing people, we cannot assume that standing people would feel uncomfortable at the temperature set for sedentary people. Instead, the 0.1 met increase for the standing people from the sedentary, and the 0.9 K preferred ambient temperature decrease means that the standing people would find the temperature for sedentary acceptable.

Under the two treadmill test conditions, the current study showed that the preferred ambient temperatures are lower than the temperature for sedentary. However, when using treadmill, there is a tendency that people are less sensitive to ambient temperatures. Therefore, whether the warmer ambient temperature set for the sedentary is unacceptable or not by the people using treadmill is unknown. Also, a fan can be used for the people with treadmill workstations. Previous studies by Zhai et al. [42] [43] have demonstrated that fan is very effective providing comfort for slight high met people in office environments, and high met people at sport facilities.

HR had been used regularly as a way to predict metabolic rate. In a study by Zhang et al. [44], they show that metabolic rate could be predicted from HR using linear regression using data obtained from 21 human subjects for HR ranges from 50 to 210 beats/min. However, in the current study, the linear relationship does not exist. From SED to STD, the HR increased significantly from 77 bpm to 90 bpm, while the metabolic level only increased 0.1 met, from 1 to 1.1 met. The HR values were very similar for STD (90 bpm), TRD1 (93 bpm), and TRD2 (93 bpm), while the metabolic rate increased significantly from 1.1 to 1.9 and 2.5 met. The high HR under standing condition could be caused by mental activities involved in the study. The subjects participated the study were not used to standing when performing office work which could cause increased HR. In fact, for the linear equations presented in ISO 8996 on estimating metabolic rate based on HR, it is recommended to use these equations only for HR higher than 120 beats/min. Because below this value, metal component cannot be neglected for work which involve mental activities, which does not follow a linear relationship [31].

It is worth noting limitations in the current study. The current study was conducted in winter using only Chinese young college-age students as human subjects. Further studies using subjects of different ethnic background, geographic locations and should be explored in different seasons. Age and gender may also affect both thermal responses and preferred temperature with standing and treadmill workstations, due to the relative smaller sample size this couldn't be compared with a firm conclusion in the current study, although young females seemed to prefer slightly warm temperatures, and had lower comfortable evaporative heat loss than young males. This need to be studied further with larger sample size.

5. Conclusions

1. Standing and typing activity shows negligible increased in metabolic rate, while walking on a treadmill workstation significantly increased human metabolic level from sedentary. Measured metabolic rate for SED, STD, TRD1 and TRD2 were 1.0 ± 0.2, 1.1 ± 0.2, 1.9 ± 0.3 and 2.5 ± 0.3 met, respectively.
2. Preferred ambient temperature decreases as metabolic rate increases. At SED, the preferred ambient temperature was 25.9 ± 0.9 °C. Preferred temperature at STD (25.0 ± 1.0 °C) decreased over SED by 0.9 °C, at TRD1 (24.1 ± 1.5 °C) by 1.8 °C, and at TRD2 (23.2 ± 1.1 °C) by 2.7 °C.
3. Subjects preferred neutral to slightly warm thermal sensation with sedentary and elevated activity levels in winter. The thermal acceptability and comfort were well-maintained at the preferred temperatures.
4. Subjects preferred lower mean skin temperature with active workstation and higher evaporative heat loss than with sedentary workstation.
5. PMV predicted much cooler ambient temperatures for elevated metabolic rate. The finding from the current study could be used as references in designing indoor environmental for spaces employed active workstations for metabolic rate from 1.0 to 2.5 met.
6. A single temperature setting in spaces with active workstations may not satisfy all occupants, thus providing personal comfort control to keep comfort might be necessary.

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