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Experimental study on thermal sensation of people in moderate activities

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A R T I C L E I N F O

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A B S T R A C T

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

1. Introduction

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

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

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

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

2. Methodologies

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

2.1. Participants

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

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

2.2. Design of experiments

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

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

2.2.1. Design of questionnaires

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

2.2.2. Arrangement and time schedule

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

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

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

2.3. Physiological and physical measurements

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

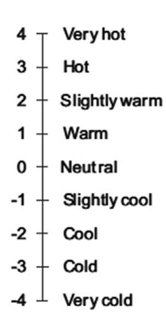

Fig. 1. Thermal sensation scale used in the experiments.

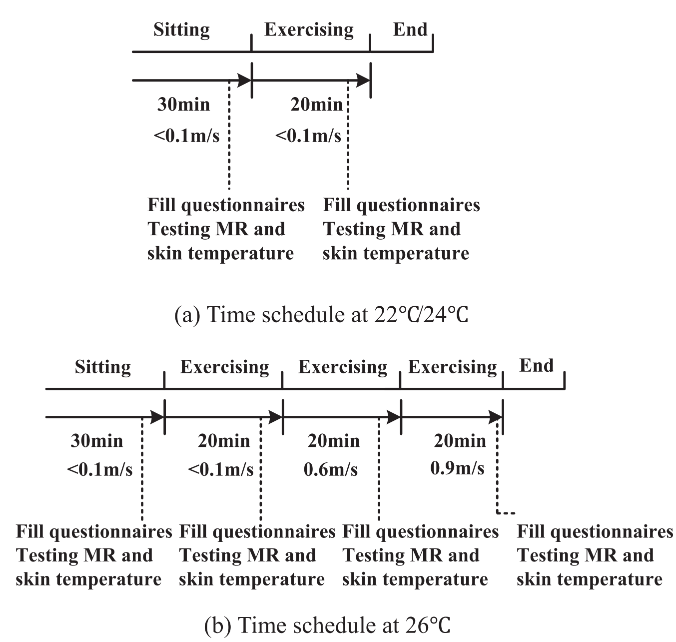

Fig. 2. Time schedule of experiments.