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Experimental research of online monitoring and evaluation method of human thermal sensation in different active states based on wristband device

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A B S T R A C T

Existing automatic control of building thermal environments do not consider the individual's real-time thermal sensation, which could reduce the occupants' thermal comfort. Therefore, it is very important to accurately obtain an individual's thermal sensation and real-time reflect on the control logic of air-conditioning systems. Current thermal sensation estimation models mostly apply to sedentary condition without considering human sensation in different activity states, which caused these models have critical limitations in accurately predicting human thermal sensation. In this paper, an intelligent wristband device is used for online monitoring of human thermal characteristics in different active states. The wrist skin temperature and its time differential as well as the heart rate are used for the evaluation index of human thermal sensation, and a series of environmental chamber experiments are carried out to obtain the relationship between the wrist skin temperature and thermal sensation in different activity states in summer. The correlation models of human thermal sensation, wrist skin temperature and its time differential, and heart rate has been formulated by statistical analysis and correlation analysis. In order to verify the feasibility of correlation models in the unstable environmental condition, several tests were conducted in the actual built environment. This study indicates that the wrist skin temperature and its time differential and heart rate can be used for estimating human thermal sensation with a high degree of accuracy in the different activity states. In addition, results of this study also demonstrate the promising applicability of obtained correlation models in the unstable environmental condition.

1. Introduction

The building thermal environment does not only impact the comfort and health of the human body, but also impacts the building's energy consumption and pollutant emission. The automatic control of the building thermal environment should be based on meeting the requirements of human thermal comfort. However, the default setting of existing building thermal environment generally determined by relevant design criterion and the automatic control systems of heating, ventilation and air-conditioning (HVAC) systems are usually based on the assumption of occupants' thermal sensation, which resulted to higher energy consumption than those based on estimated thermal sensation [1]. Some building automatic systems are also controlled based on the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) thermal comfort model, such as Predicted Mean Vote (PMV) [2]. These models mainly rely on empirical recommendations or predefined formulas, but do not take the individual's physiological characteristics into consideration [3–5]. Therefore, it is very important to accurately obtain an individual's thermal sensation and reflect it on the control logic of air-conditioning systems in real-time.

During the research, the human factors, such as clothing condition, active state and environmental preferences, always change in real-time, which will lead to unpredictable thermal sensation. In order to develop models to estimate personal thermal sensation, many researchers have used different physiological signals. Wang [6] used upper extremity skin temperatures, such as hand, finger, and forearm, to predict people's thermal state and explore the correlation between upper extremity skin temperatures and overall thermal sensation. Nakayama et al. [7] focused on the peripheral skin temperature for thermal sensation estimation and proposed an estimation method that can predict individual thermal sensation by monitoring the finger skin temperature. Sugimoto [8] proposed a wearable system to measure biological data, activity data and location data of humans in daily life. The wearable system consists of a tympanic temperature sensor, an electrocardiogram sensor with a tri-axial accelerometer and thermo-hygrometers, and

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skin temperature sensors. Ghahramani et al. [9] selected human face skin temperature as a physiological signal because of its high density of blood vessels. They presented a novel infrared thermography based technique to obtain an individual's thermal comfort and thermoregulation performance by monitoring several points of the face skin temperature. Xiong et al. [10] investigated seven local parts of human body to study the relationship between thermal perception and skin temperature under the condition of different transient thermal environments. Sim et al. [11] invented a wrist-type wearable device to simultaneously monitor the wrist skin temperatures, and they also assessed the feasibility of wrist skin temperature monitoring for human thermal sensation estimation. Zhang et al. [12] described a thermal sensation model based on skin temperature data measured from 19 individual body parts, and they have found that the local sensation would be related to both local and whole body skin temperature. Choi and Yeom [13,14] established a skin temperature-driven thermal sensation model by monitoring a significant and minimum number of the local body area. They also found the optimal combinations of local body segments that could represent the overall thermal sensation with a high degree of accuracy.

A large number of wrist-type wearable devices that can monitor physiological characteristics, such as wrist skin temperature and heart rate, have emerged and many researchers have focused on the feasibility of using wrist skin temperature to estimate human thermal sensation. Choi's research found that the wrist would be the most representative body location for thermal sensation estimation, but the estimation model that calculates based on wrist skin temperature was not given [15]. Sim et al. [11] verified the feasibility of wrist skin temperature in human thermal sensation estimation, and they developed some thermal sensation models by monitoring the wrist and fingertip skin temperatures. However, the studies have some limitations because the sample size was small and the finding may only be suited for the symmetric condition. Choi and Yeom [13] have found that the wrist skin temperature and its changing rates provided a higher accuracy than other body areas' skin temperature for the thermal sensation estimation when only a single body segment was considered.

However, these studies primarily focused on only one activity level, such as sedentary or minor activity. The human thermal comfort is subjective and multi-factor dependent and metabolic rate is one of the significant factors for thermal comfort [16,17]. Therefore, some of the research findings may be somewhat limited in different activity conditions. In addition, in order to reflect individuals' thermal sensation on the control logic of air-conditioning systems, the parameters of establishing thermal sensation estimation models should be obtained easily. Besides, it is really important to verify the feasibility of the estimation model in actual indoor environment because the actual automatic control of air-conditioning systems is an unstable environmental condition, which is different from the environmental chamber. Moreover, many studies have identified that heart rate is a potential indicator that can be used for thermal sensation estimation, but current human comfort models almost focus on skin temperature without considering the heart rate [18–20]. Choi et al. [19] demonstrated the possibility of using heart rate as a parameter for human thermal sensation estimation, but they did not develop any mathematical model.

Therefore, this paper aims at online monitoring of human thermal characteristics based on wristband device and developing the thermal sensation estimation models of the human body in different active states by experimental research in summer. This study also attempts to introduce the heart rate as another parameter for developing human thermal sensation estimation model under the different active states. The rest of this paper is organized as follows: Section 2 provides a description of experiment condition, including experiment chamber, equipment, experimental procedure, and methods of statistical analysis. Section 3 analyses the experimental results. Based on the study findings, this section also established several thermal sensation estimation models with different parameters. In addition, several tests were conducted in the actual built environment to verify the feasibility of correlation model in the unstable environmental condition. Section 4 discusses the obtained results and presents some limitations of this study as well. Section 5 lists the conclusions.

2. Methods

2.1. Experimental chamber and equipment

A series of human subjects experiments were carried out to collect human thermal sensation and thermal characteristics at the environment chamber of Dalian University of Technology in China. The floor plan of environment chamber, which consists of a 5.7 m × 6.3 m laboratory and a 2.8 m × 6.3 m HVAC system space, are illustrated in Fig. 1. The variable air volume (VAV) system was equipped to control the building thermal environment and indoor air quality.

In addition, many sensors were installed in the laboratory, including CO_2 sensor, air temperature and humidity sensor, and air velocity sensor. The temperature can be controlled within the range of 0.1 °C, which meets the requirements of control accuracy. The air velocity was controlled at less than 0.2 m/s, as suggested by ASHRAE Standard 55 [2]. In order to release the influence of indoor air quality, the concentration of CO_2 was controlled under 800 ppm according to ASHRAE Standards 62.1 [21]. The wristband device consists of a skin temperature sensor and a heart rate sensor, which can be used for online monitoring human thermal characteristics. All the temperature sensors are calibrated by the temperature verification box. The model and specification of all equipment are shown in Table 1.

2.2. Experimental procedure

The basic information about the participants, such as age, weight, height, body mass index (BMI), and gender were surveyed before the experiments. The information about the human subjects used for the final analysis is shown in Table 2.

Ten healthy subjects including six men and four women participated in this study. In order to minimize the influence of heat acclimation, all subjects were graduate students who have lived in Dalian for more than 2 years. Their physiological condition was normal, without any illnesses such as a cold or a fever. Their psychological condition was stable and had no mood swings during the experiments. The human subject experiments were carried out at least an hour after the subjects had eaten food or had done strenuous exercise. The overall flow chart of research is illustrated in Fig. 2. Since the target of this study is developing the correlation model between thermal sensation and thermal characteristics of human body under different active states for building thermal environment control, each subject wore a short sleeve T-shirt with no jacket and trousers during the experiments. The numerical value of the clothing insulation was approximately 0.57 clo.

The time schedule of experiments is shown in Fig. 3. Previous studies [13–15] have conducted the human sensation experiments under indoor temperature range of 20–30 °C. In these experiments, we also prepared to control the indoor temperature from 20 °C to 30 °C. However, some female subjects cannot bear too cold indoor temperature, thus we scrapped the experiment under the indoor temperature of 20 °C. The experiments were divided into two parts: cold condition (Fig. 3(a)) and warm condition (Fig. 3(b)). The indoor temperature decreased from 26 °C to 22 °C on the cold