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Study of data-driven thermal sensation prediction model as a function of local body skin temperatures in a built environment

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ABSTRACT

Current thermal/sensation models primarily rely on predefined formulas or empirically defined recommendations, but fail to consider each individual's physiological characteristics. Such models frequently ignore occupants' diverse physical conditions and, therefore, have critical limitations in estimating each individual's thermal sensation levels. Since the human body is governed by the thermoregulation principle to balance the heat flux between the ambient thermal condition and the body itself, skin temperature has a significant role in maintaining this physiological principle. Therefore, this study investigated the potential use of skin temperature and its technical parameters in establishing a thermal sensation. By using advanced modern sensing technologies, and existing thermal regulation model research, this study selected and validated seven body areas as significant local body segments for determining overall thermal sensation. A series of environmental chamber tests were conducted for 2 h. While the indoor temperature fluctuated between 20 °C and 30 °C, skin temperatures of the seven selected body areas were measured in conjunction with a thermal sensation and comfort survey. Results of this study revealed that combinations of skin temperatures for the arm, back, and wrist provided the significant information needed to accurately estimate the thermal sensations of each user. Most of all, both sides of the wrist generated accurate data more than 94% of the time.

Therefore, considering the modern advanced wearable sensing technologies, results of this study confirmed that optimum combinations of skin temperature information from selected body areas, is reliable and generally applicable for estimating individual thermal sensations.

1. Introduction

For indoor thermal control, modern building systems are controlled based on existing thermal sensation/comfort models, such as ASHRAE-PMV [1]. These primarily rely on predefined formulas or empirically defined recommendations, but do not consider each individual's physiological characteristics, such as gender, age, body mass index, etc. [2–8], that have been investigated as significant parameters that affect thermal sensations. Predefined thermal comfort models ignore diverse physical conditions (such as varying comfort ranges) and have critical limitations in satisfying individual thermal comfort preferences. For this reason, the rate of thermal dissatisfaction expressed by building occupants in the U.S. is higher than 60%. The top ranked complaints concern being “too cold” during the summer, and “too warm” during the winter, even though temperatures are within the comfort ranges defined by industry standards [1,9,10]. Considering the energy efficiency impact of an indoor set-point temperature at 1.5% of the total energy consumption for HVAC, per 1 degree of Fahrenheit change [11,12], this is a significant energy conservation opportunity that will also enhance each occupant's thermal satisfaction. Therefore, it is very crucial to accurately identify thermal sensation/comfort levels that could enhance each occupant's physiological and environmental preferences.

With the help of advanced modern sensing technologies, multiple efforts are being made to investigate such human physiological signals and to consider their relation to thermal sensations or ambient temperature conditions. Yao et al. [13] conducted experiments with human subjects to identify the relationships between local thermal sensation, thermal comfort, and skin temperature distribution on the body by adopting Colin/Houdas, Hardy/DuBois, Stolwijk, and Mitchell/Windham models. Yao's study focused on

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validating those existing models by comparing their collected skin temperature data with the existing PMV model (as a baseline). Zhang et al. [14] developed a thermal sensation model, based on skin temperature data measured during chamber tests, where thermal conditions were not uniform. Zhang's study focused on the applicability of these data in a vehicle environmental setting, which was not compatible with a building environment. Even though Yao's [13] and Zhang's [14] studies adopted human factors and skin temperatures, the generated models were designed based on averaged data in the form of a mathematical equation. Choi et al. [5] and Sim et al. [15] revealed that skin temperatures measured at the wrist provided significant information for translation into a user's thermal sensation. However, validation of Choi's and Sim's studies was limited because of small sample sizes and restrained accuracy levels. Liu et al. [16] studied human skin and surface temperatures in a stable and an unstable thermal environments. Liu's study revealed that the effect of air and radiant temperature on skin temperature varied, and the human body could not become thoroughly physiologically stable within 40 min. However, Liu et al. focused on human physiological conditions, rather than the relationships between thermal sensation/comfort conditions and skin temperatures. In addition, the current thermoregulation models (that estimate local body temperature as a function of ambient environmental conditions) have no consistent selection points on the human body. Although some specific areas have been consistently selected in those models, each model adopts a different weight factor, per selected local body or body segment, to estimate the overall body temperature or thermal perception.

Therefore, even though multiple studies used human physiology and an averaged overall thermal sensation, as a function of skin temperatures collected from multiple body points, those studies focused on the physiological relationship between ambient thermal conditions and the human skin temperature reaction. This approach is significantly limited for practical application.

Thus, the purpose of this study was to identify a significant and minimum number of local body areas that can generate the most significant skin temperatures to accurately estimate a user's thermal sensation by considering physiological characteristics, such as gender and body mass index. Based on study findings, this research

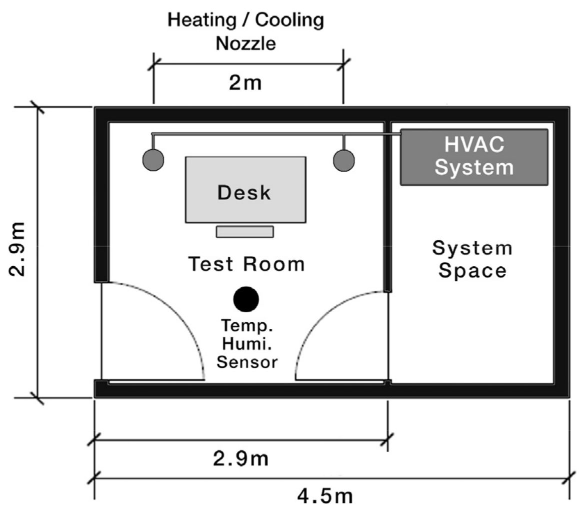

Fig. 1. Floor plan of the experimental chamber.

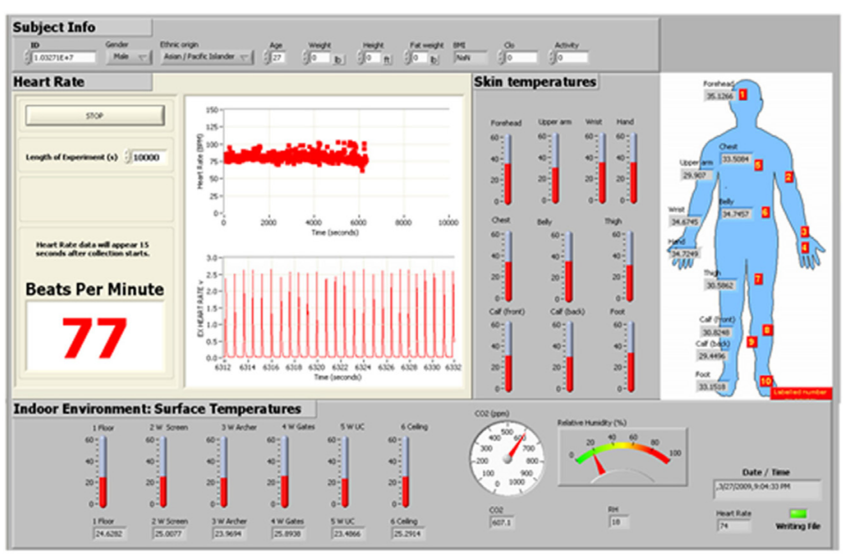

Fig. 2. Data acquisition interface for skin temperature and indoor environment.

Table 1
Specifications for data acquisition equipment.

Sensing Equipment	Model	Specification
Indoor temperature sensor	LM35DT	Accuracy: ± 0.5 °C, Resolution: 0.01 °C
Skin temperature sensor	SBS-BTA	Accuracy: ± 0.5 °C, Resolution: 0.03 °C
Air velocity sensor	Testo 405-V2	Accuracy: ± 5 °C, Resolution: 0.01 m/s
CO_2 sensor	Telarire 6004	Accuracy: ± 40 ppm
Humidity sensor	HIH-4000-003	Accuracy: 3.5%, Resolution: 0.5%
Data acquisition board 1	Sensor DAQ	Resolution: 13 bit, Sampling rate: 10 kS/s
Data acquisition board 2	NI-DAQ 6008	Resolution: 12 bit, Sampling rate: 10 kS/s