学 位 論 文 内 容 の 要 旨

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学 位 論 文 題 名

Real-time Thermal Sensation Prediction Incorporating Individual Differences via Thermal Comfort Models and Physiological Responses

(温熱快適性モデルと生理反応を用いた個人差を考慮したリアルタイム温冷感予測)

Thermal comfort is a subjective assessment of the surrounding thermal environment, encompassing both physiological and psychological responses. Environmental parameters like air temperature, relative humidity, air velocity and mean radiant temperature play a dominant role in shaping individual thermal perception. In addition, personal variables such as metabolic rate (M) and clothing insulation (I_{cl}) are also significant determinants that substantially influence an individual’s thermal comfort experience. Thermal perception aligned with thermal comfort enhances immediate satisfaction and contributes to long-term benefits, including increased productivity and heightened efficiency.

Traditionally, thermal comfort assessments are subjective measures, and true assessments can be executed through questionnaire surveys. However, it is mostly impractical to conduct continuous monitoring in real-world. To address these limitations, various mathematical models were developed. Among them, the predicted mean vote (PMV) model is the most widely adopted model which relies on the basic concept of the human body’s heat balance with the surrounding thermal environment. Specifically, it considers all four key environmental parameters as well as individual factors. In addition, due to the strong alignment between its prediction scale and actual subjective thermal sensation votes (TSV), the PMV model remains the most used technique for assessing thermal sensation. However, due to the complexity and time-consuming nature of assessing M and I_{cl}, these personal factors are often presumed as constant values. For example, for sedentary activities, M is considered as 1.2 MET. While I_{cl} estimation is done typically based on standard basic clothing ensembles. This simplification leads to a significant discrepancy between TSV and PMV, thereby reducing the accuracy of estimations.

Alternative way to assess thermal sensation is physiological responses to the thermal environment. Important physiological indicator closely associated with thermal sensation is skin temperature (t_{sk}). However, accurate measurement requires direct sensor attachment, which limits its workability for continuous observation.

Another important consideration in thermal comfort assessment is the influence of individual differences on thermal perception. Factors such as gender, body mass index (BMI), and susceptibility to cold constitution (hie-sho) have been shown to play a considerable role in thermal perception. Even under thermoneutral conditions, these individual characteristics can lead to notable alterations in thermal sensation. Moreover, the same individual may perceive identical environmental conditions differently depending on their activity level, degree of thermal adaptation, or physiological state at a given time.

Considering the above-mentioned issues, primarily this research aimed to develop an accurate and simplified method for predicting PMV to estimate TSV more precisely and comprehensively. To achieve this, infrared thermography (IRT) was employed as a non-intrusive real time assessment tool. Specifically, this study utilized IRT to predict I_{cl}, based on evaluating clothing surface temperature (t_{cl}) and t_{sk}, which eventually used to predict *PMV*. In addition, morphological characteristics were utilized as a simplified approach to estimate M.

Furthermore, this research work also explored individual differences in thermal perceptions, *PMV*, t_{sk}, and temperature gradients between proximal and distal body ($\Delta\ t_{proximal-distal}$) to better understand their impact on subjective thermal responses.

It was observed that, TSV and $\Delta\ t_{proximal-distal}$ were strongly correlated. Based on it, this research proposed a novel method of thermal sensation prediction (*TSP*) to predict TSV in real-time using IRT.

This dissertation systematically documents the research undertaken and is structured into the following six chapters:

Chapter 1: General introduction

This chapter introduces the fundamental aspects of the research work, outlining the background, identifying research questions, existing challenges, defining the research objectives and hypotheses.

Chapter 2: Literature review

This chapter presents a comprehensive review of the literature related to thermal comfort and thermal sensation, methods for estimating thermal comfort, current advancements and highlights the role of individual differences in influencing thermal perception.

Chapter 3: Investigating real-time thermal sensation prediction, using predicted mean vote (*PMV*). (Study 1)

This chapter evaluates the accuracy and practicality of various techniques, with particular attention to the integration of infrared thermography to predict *PMV*. It was observed that IRT estimated *PMV* performs better in TSV prediction than the traditional approaches.

Chapter 4: Predicting individual variability in thermal sensations, predicted mean vote (*PMV*) and predicted percentage of dissatisfied (*PPD*) and local skin (t_{sk}) temperature differences (Study 2)

This chapter investigates the impact of individual morphological and behavioral differences on thermal sensation. It also explores the interrelationships among these individual characteristics and their influence on thermal comfort responses. Notable individual differences were identified in thermal perception as well as in physiological responses.

Chapter 5: Assessing physiological responses to develop a real-time thermal sensation prediction model (Study 3)

This chapter investigates the physiological responses in different climatic conditions and their association with thermal sensations. It also proposes a model to assess thermal sensation in real time based on physiological responses.

Chapter 6: Summary and future perspectives

The final chapter summarizes the key findings of the research, implications in practical scenarios and outlines potential directions for future research in personalized thermal comfort assessment.