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Physiological Response of Human Body and Thermal Sensation for Irradiation and Exercise Load Changes

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1. Introduction

With the occurrence of the heat island phenomenon, the thermal environment surrounding urban residents is deteriorating. When evaluating the thermal comfort in an outdoor environment, the instability associated with movement in space and changes in the weather could not be ignored. Especially, the changes in the amount of radiation to the human body and the changes in the metabolic rate of the human body are higher than the amount of change estimated for an indoor environment. In the steady state, a thermal index based on the human thermal load has been proposed by Shimazaki et al. (2009), yet studies focused on the instability in an outdoor environment are not common. In this research, we aimed to design an unsteady thermal comfort index in an outdoor space considering the physiological and psychological responses of humans. We conducted human subject research under conditions in which the amount of radiation and metabolic rate change with time, which in turn have a large impact in an outdoor space. On the basis of the results, the explanatory variables are extracted, and the prediction of an unsteady thermal sensation was formulated.

2. Experimental method

In this research, we conducted a human subject experiment, in which the radiation and exercise load change with time. The parameters measured from the environmental conditions surrounding the subjects were the air temperature, relative humidity, wind speed, and amount of radiation. As physiological information of the subject, the skin temperature, deep body temperature (eardrum temperature), heart rate, breathing metabolic rate, weight, and blood flow were measured.

The subjects' clothing consisted of a T-shirt, shorts, and white running shoes, with the thermal insulation property of clothing being 0.3 clo. As for the thermal sensation, on the basis of the Japanese translation of the ASHRAE thermal index, subjects were asked to mark on a linear scale of "very cold (-3), neutral (±0), and very hot (+3)." Subjects were asked to report their thermal sensation every three minutes in radiation and exercise load experiments and every five minutes in an experiment with both radiation and exercise loads.

2.1 When the radiation load changes with time

Experiments were conducted on November 29 and December 2, 2013 in the artificial climate chamber at the Technology Research Institute of Osaka Prefecture. The parameters were as follows: an air temperature of 28 °C, a relative humidity of 50%, and a weak wind. A metal-halide lamp was used, which had an irradiance of 1000 W/m^2 at the solar radiation wavelength (a height of 150 cm). Subjects moved between the lamp-irradiated area (in sunlight) and a neighboring area that was not irradiated with the lamp (shade) in intervals of three or nine minutes. Subjects were the same ten male students for all conditions.

2.2 When the exercise load changes with time

The experiments were conducted from July to September 2014 in the artificial climate chamber at Kansai University. The parameters were as follows: an air temperature of 28 °C, a relative humidity of 50%, and a weak wind. As the exercise load, 90 W of load was applied through a bicycle exercise with a bicycle ergometer. By switching between nine minutes of exercise and three minutes of rest, the amount of work was changed in steps. In addition to the above-mentioned conditions, five more conditions were used for the experiment: 1) the relative humidity is 30% (90W30%RH condition), 2) the amount of work by the ergometer is 120 W (120 W condition), 3) the amount of work by the ergometer is 60 W (60 W condition), 4) the rest time is nine minutes (long cycle condition), and the water intake is restricted for 5 h prior to the experiment (water restriction condition). Under

90W30%RH and 90W50%RH conditions, the same six subjects were used for the experiment. In all the other conditions, the same two subjects were used for the experiment.

2.3 When both radiation and exercise loads change

The experiments were conducted at the Osaka Prefecture University campus on September 2 and 3, 2014. Changes in the radiation load (by moving between the shaded area covered by trees to the sunny areas in an open space) and changes in the exercise load (by switching between a standing rest state and walking back and forth) were applied to the subjects. The walking speed was set at 1 m/s. Figure 1 shows the experimental schedule. Subjects were the same four people over two days.

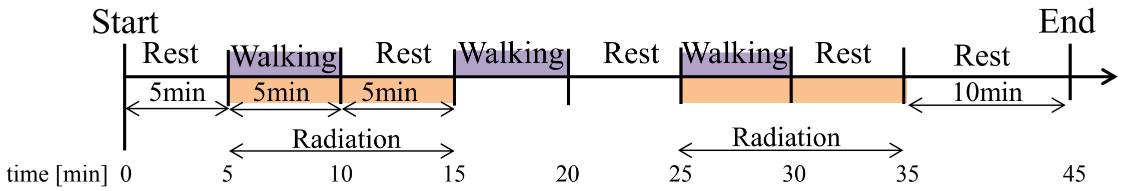

Fig. 1 Experimental schedule.

3. Experimental results and discussion

The physiological values of the subjects in a steady state prior to the application of a load are used as the initial values. The deviations in the mean skin temperature from the initial condition is defined as T'_{skin} [°C], and the deviation in deep body temperature from the initial condition is defined as T'_{cor} [°C]. In addition, the change in the skin temperature over three minutes is defined as ΔT_{skin} [°C].

3.1 When the radiation load changes with time

Figure 2 shows the correlation between ΔT_{skin} [°C] and the change in the thermal sensation. A linear correlation was observed between ΔT_{skin} [°C] and the change in the thermal sensation. On the basis of these results, we believe that the change in the skin temperature is an important factor in the thermal sensation of a human body.

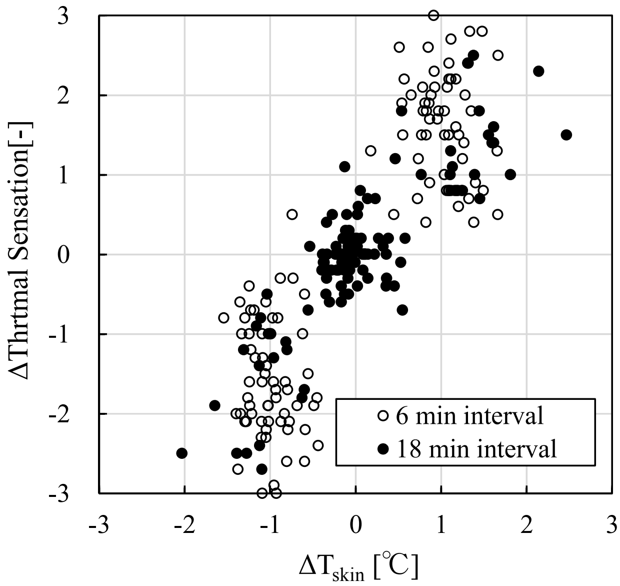

Fig. 2 Correlation of ΔT_{skin} [°C] and the change in the thermal sensation.

3.2 When the exercise load changes with time

Figure 3 shows the correlation between the thermal sensation at a certain time and the mean skin temperature six minutes after the thermal sensation is reported. The correlation coefficient at this time is higher than the correlation between the reported value of the thermal sensation and the mean skin temperature that was measured at the same time. Thus, it may be more suitable as an explanatory variable against changes in the thermal sensation.

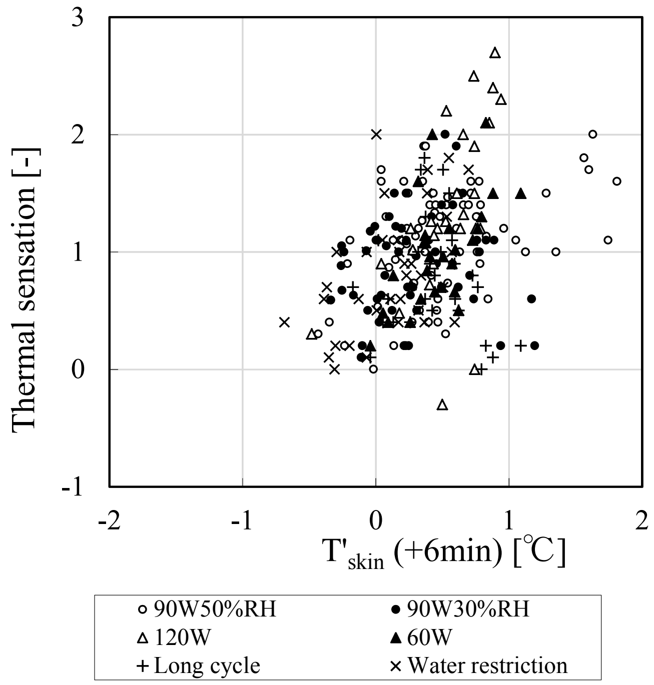

Fig. 3 Correlation between the thermal sensation and the mean skin temperature six minutes after the thermal sensation was reported.

4. Prediction of the unsteady thermal sensation by a physiological prediction model

We calculated the thermal sensation by a multiple regression analysis that uses physiological values as the explanatory variables. It is said that the mean skin temperature and deep body temperature express the thermal state of a human body in a steady state. From the radiation load experiment, the changes in the skin temperature exhibited a higher correlation with the thermal sensation, whereas the heart rate exhibited a higher correlation with the thermal sensation in the exercise load experiment. On the basis of these results, we added the deviation in the metabolic rate from the initial value, M' [W/m^2], to the explanatory variables of the multiple regression analysis: T'_{skin}, ΔT_{skin}, and T'_{cor}. In the metabolic change experiment, we used T'_{skin}, measured three minutes after the thermal sensation was reported, as the explanatory variable, as it has a higher correlation than initial T'_{skin}. Equation (1) shows the radiation load in the prediction formula for the unsteady thermal sensation, and Equation (2) shows the exercise load in the same situation, where PTS (Rad) and PTS (Metabo) are deviations from the initial thermal sensation when the radiation load and exercise load are applied, respectively.

Equation (3) shows the prediction formula of the unsteady thermal sensation when both radiation and exercise loads change, where PTS (Rad + Metabo) is the deviation from the initial thermal sensation. We implemented an outdoor experiment, in which the radiation and exercise loads changed at the same time, examined the relationship between the thermal sensation value reported by the subjects, and predicted the thermal sensation from Equation (3). The results were roughly similar to the thermal sensation values reported by the subjects, indicating that the thermal sensation prediction formula from a single load change can lead to a prediction of the comprehensive load changes.

$$PTS(Rad) = 0.79T'_{skin}(t) + 0.39\Delta T_{skin}(t) \quad (1)$$

$$PTS(Metabo) = 0.6T'_{skin}(t+3) + 0.71T'_{cor}(t) + 0.0043M'(t) \quad (2)$$

$$PTS(Rad + Metabo) = \frac{1}{2}\left\{0.79T'_{skin}(t) + 0.67T'_{skin}(t+3)\right\} + 0.39\Delta T_{skin}(t) + 0.71T'_{cor}(t) + 0.0043M'(t) \quad (3)$$

We introduced a perspiration model by Minami et al. (2008), which incorporates the metabolic rate, to the two node model by Gagge et al. (1986) in order to perform calculations. The thermal sensation values reported by the subjects of the radiation load experiment and exercise load experiment were expressed by the mean value of all subjects. In the experiment with both radiation and exercise loads, the climatic conditions were different in every experiment; thus, we analyzed the experiment conducted during the time frame with strong sunlight as a representative. Figure 4 shows the reported thermal sensation values of the radiation load experiment and the predicted thermal sensation from Equation (1), Figure 5 shows the thermal sensation values reported in the metabolic rate change experiment and the predicted thermal sensation from Equation (2), and Figure 6 shows the thermal sensation values reported in the experiment with both radiation and exercise loads and the predicted thermal sensation. The results show that the thermal sensations were accurately predicted in all cases.

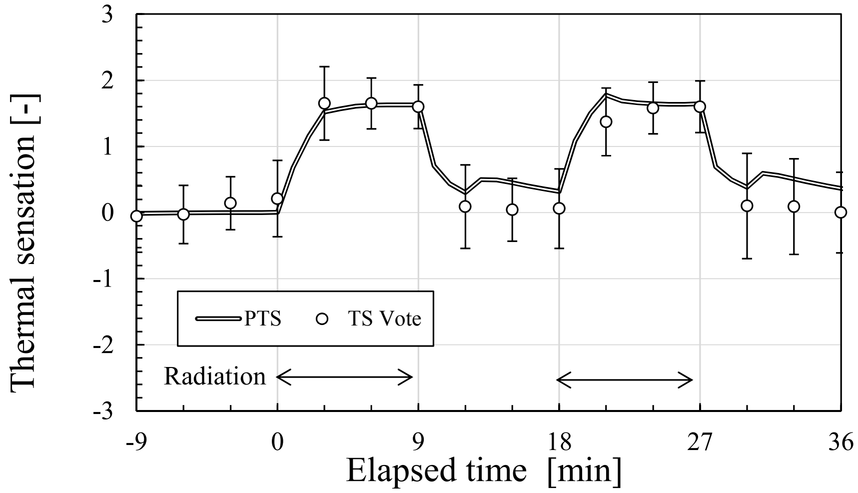

Fig. 4 Reported thermal sensation values and predicted thermal sensation from the radiation load experiment.

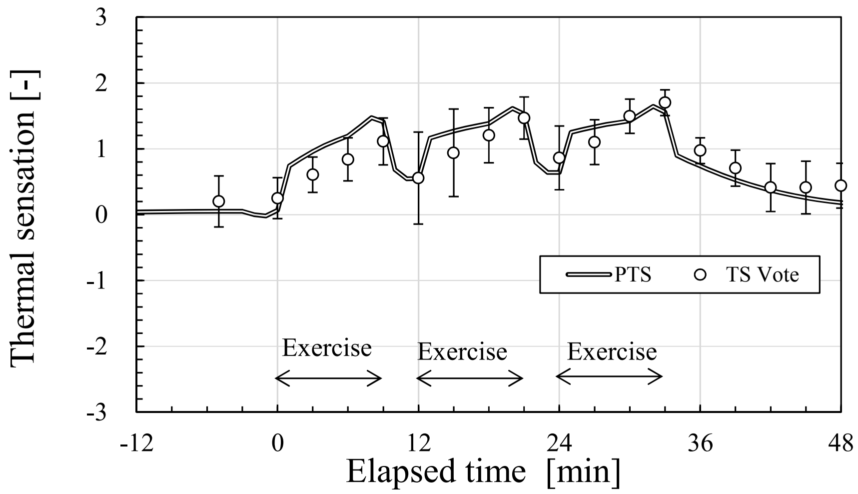

Fig. 5 Reported thermal sensation values and predicted thermal sensation from the exercise load experiment.

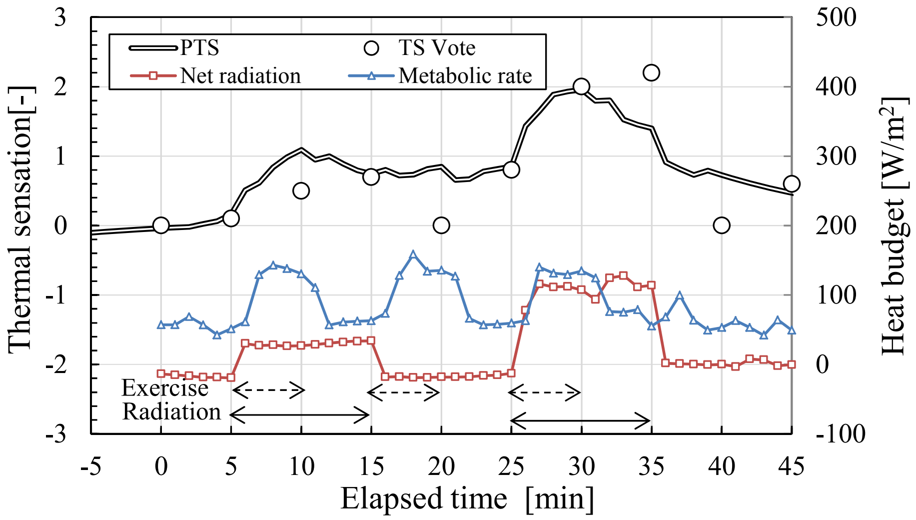

Fig. 6 Reported thermal sensation values and predicted thermal sensation from the experiment with both radiation and exercise loads.

5. Conclusion

In this research, we conducted a human subject experiment to create an evaluation index for an outdoor thermal environment in an unsteady environment.

(1) When the amount of radiation changes, the change in the mean skin temperature of the subject and the change in the thermal sensation exhibit a strong correlation.

(2) When the metabolic rate changes, there is a time lag between the skin temperature and the thermal sensation.

(3) From a multiple regression analysis, we calculated the prediction formula for the unsteady thermal sensation. Even under conditions in which both the change in the amount of radiation and the change in the metabolic rate are added, the thermal sensation can be predicted under an unsteady condition.

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