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Evaluation of Contact Thermal Sensation Caused by Local Stimulation with Seating in Outdoor

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The experiments on contact thermal sensations felt by subjects were performed under two conditions, namely, when seated outside and in an artificial climate chamber. There was a high correlation between the contact thermal sensation and the seat surface heat flux for thermal stimulus in a hot environment. It could be quantified that the effect of the thermophysical properties of a seating surface material on the contact thermal sensation. For cold stimulation in a cold environment, the trends that were seen for hot stimulus in the hot environment could not be observed. It was concluded that this was due to the large contact thermal resistance arising from the differences in insulation performance of clothes. In an outdoor environment dominated by solar radiation, the effect of contact thermal sensation on the whole-body thermal sensation could not be comfirmed.

1. Introduction

In recent years, to improve the thermal sensation in indoor spaces, personal air conditioning systems [1] that perform local heating and cooling based on the thermal sensations of individuals and thermal control that takes into consideration the heat transfer through parts in contact with an individual, such as a floor surface and seat surface, have attracted attention. Matsumoto et al. [2] studied the influence of such contacts on the whole-body thermal sensation by assuming that floor panel heating would heat the sole of the foot. Compared to when there was no floor panel heating, there was a difference in the contact thermal sensation and whole-body thermal sensation when the sole of the foot was heated. Naka et al. [3] reported that there was a significant change in the whole-body comfort when the temperature of a car seat was adjusted. This was thought to be due to the large contact area between the seat and the body. In each of these studies, the level of skin stimulation had not been sufficiently evaluated; thus, there is no clear quantitative relationship between stimulation level and local thermal sensation.

Outdoor spaces have lately provided increasing opportunities to study thermal environment control via adaptive measures such as sun shades and window films [4-5]. The introduction of wooden chairs is being promoted, even at outdoor stadiums, for the purpose of improving user comfort [6]. Wooden materials have useful thermophysical properties, such as low thermal conductivity and low thermal effusivity. Because of these properties, wooden materials are expected to be effective insulating materials. Misaka et al. [7] performed human subject experiments to compare temperature perceptions; the subjects were seated outside during the summer either on a bench whose temperature could be adjusted using flowing water (cooling bench) or on an ordinary bench without cooling. They observed that when subjects sat on the cooling bench for a certain duration, the whole-body thermal sensation reported when sitting on the normal bench was alleviated. The salient drawbacks of this study were that the seat surface temperature had not been set; the seat surface heat flux, namely, level of stimulation on skin was not measured; and the local thermal sensation here, namely, the thermal sensation on the buttocks was not evaluated. These constitute the future challenges for their study.

Shimazaki et al. [8] conducted a study on the local thermal sensation on different locations of the body for cold stimulation. They reported that the body trunk was more sensitive than the limbs at perceiving differences. In human subject experiments conducted in an artificial climate chamber, they indicated that there was a correlation between whole-body thermal sensation and local thermal sensation. Obata et al. [9] calculated the contact surface temperature from analysis of the heat transfer phenomenon when two objects with semi-infinite thicknesses were in contact and showed that there was a correlation between the local thermal sensation and difference between the initial and contact surface temperatures of the two objects. Moreover, they discussed the relationship between contact thermal sensation and thermophysical properties of the objects.

In this study, we installed a plastic seat surface and a wooden seat surface in a sunny place, both inside an artificial climate chamber and in an outdoor area, and conducted experiments involving human subjects sitting on these seats. Through this study, we examined the relationship between the level of local stimulation from the seat surface on the buttocks and the associated thermal sensation. The present study intended to clarify the factors controlling buttock contact thermal sensation; relationship between contact thermal sensation, whole-body thermal sensation, and comfort; difference between susceptibilities to hot and cold stimuli; and influence of contact thermal resistance.

2. Experimental Site and Methods

The experiments were conducted outdoor and in an artificial climate chamber. The outdoor experiment used a building roof in the Nakamodzu campus of the Osaka Prefecture University and the artificial climate chamber experiments used the facilities within the Technology Research Institute of Osaka Prefecture. The artificial climate chambers were set up with lighting that simulated sunlight. The outdoor summer experiments were conducted on July 27, August 3, and August 10, 2017, and the outdoor winter experiments were conducted on December 22, 2017 and January 19, 2018. The artificial climate chamber experiments were conducted on November 30 and December 1, 2017.

The outdoor experiments were conducted on days with weak wind and stable weather. The seat surface temperature was not adjusted. The summer experiment days, on average, had a temperature of 34.2 °C, relative humidity of 45.7%, and global solar radiation of 725 W/m^2. The winter experiment days, on average, had a temperature of 11.1 °C, relative humidity of 36.1%, and global solar radiation of 560 W/m^2. The artificial climate chamber simulated a hot summer environment, with a temperature of 30 °C, relative humidity of 50%, quietness, solar radiation of 800 W/m^2 using a metal halide lamp, and the seat surface temperature was adjusted to 50 °C and 55 °C.

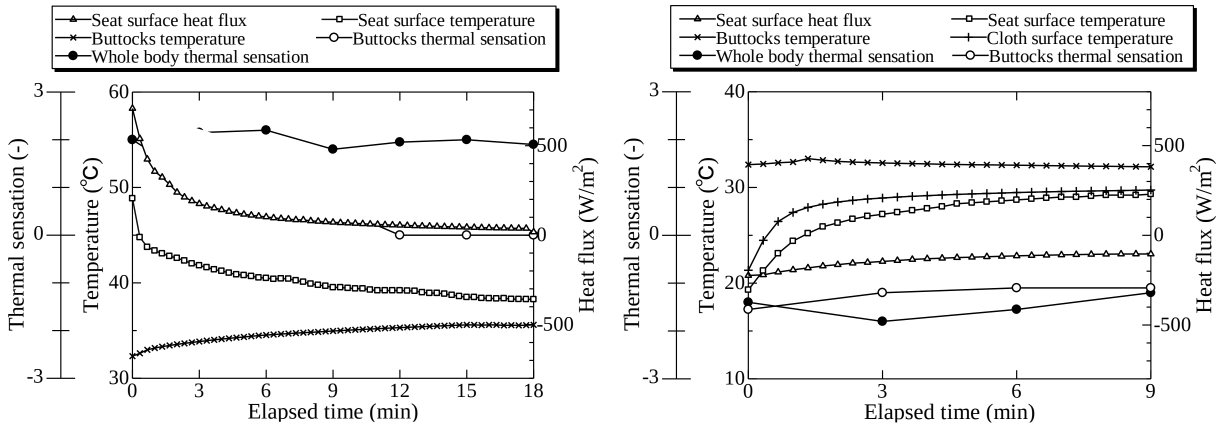
Temperature, relative humidity, solar radiation, infra-red radiation and wind speed were measured as weather condition parameters. To measure the temperature and relative humidity, we installed a sensor inside a ventilation pipe. An ultrasonic anemometer was used to measure the wind speed. They were all installed at a height of 1 m from the ground. To evaluate the level of stimulation from the seat surface, we measured the seat surface temperature using a thermocouple, its heat flux using a heat plate, and the buttock temperature using a thermistor. The clothing temperature was also measured during winter. Skin temperatures were measured at seven sites and the rectal temperature was measured as a core temperature using a thermistor. The measurement interval for all parameters, except wind speed, was 10 s; the measurement interval for wind speed was 0.1 s. To determine the total volume of sweat during measurement, we measured the body weights of the subjects at the start and end of the experiments. As psychological declarations of the subjects, we obtained their buttock thermal sensations, whole-body thermal sensations, and levels of comfort every 3 min, according to a linear scale based on the ASHRAE thermal sensation index [10].

The subjects were seven, healthy, male undergraduate and graduate students of the university, who were between 21 to 24 years. The subjects refrained from eating since 2 h prior to the start of experiment and stayed in a waiting room set to a constant temperature of 26 °C since 1 h before moving to the experimental site. After moving from the waiting room to the experimental site, the subjects spent approximately 10 min in preparation: wearing a device to measure their physiological parameters. After data was acquired for 3 min while standing at rest, the subjects sat on the seats. The seating time was 18 min for the summer outdoor experiments and 9 min for the artificial climate chamber and winter outdoor experiments. The experiments were conducted according to procedures approved by the ethics committee of the Graduate School of Engineering, Osaka Prefecture University. On top of commercially-available wooden chairs, a plastic seat surface (44×41×4 cm) and a wooden seat surface (40×39×6 cm) were placed to obtain the chairs required for these experiments. The two types of chairs were kept side-by-side, and the experiments involved two subjects sitting on the respective chairs at the same time and were conducted were repeatedly. Their chairs are representative for ordinary use. The summer and winter outdoor experiments and the artificial climate chamber experiments involved the total number of 20, 20, and 42 subjects, respectively.

3. Measured Results and Discussion

Figure 1(a) shows an example of the change over time in the seat surface heat flux where the direction from the seat surface to the buttocks is positive for the seat surface temperature, buttocks temperature, and whole-body thermal sensation that were obtained in the summer outdoor experiment. The seat surface heat flux reached its maximum immediately after sitting and converged to 0 thereafter. The buttock temperature and the seating surface temperature gradually converged to the equilibrium temperature. There was a difference in the two temperatures even after 18 min, suggesting contact thermal resistance. There were no significant changes to the whole-body thermal sensation and comfort.

Figure 1(b) shows an example of the change over time in seat surface heat flux where the direction from the seat surface to the buttocks is positive for the seat surface temperature, buttocks temperature, buttocks clothed temperature, buttocks thermal sensation, and whole-body thermal sensation that were obtained in the winter outdoor experiment. Due to the difference in season between the summer and winter experiments, there is a difference in the type of clothing worn. The summer clothing were white T-shirt and shorts, whereas the winter clothing were gray long-sleeve sweatshirt and long sweatpants. The summer clo level was 0.3, whereas the winter clo level was 1.0. For this reason, it was predicted that the contact thermal resistance is greater during winter than in the summer, and despite it being around the same temperature difference as in the summer experiment, the seat surface heat flux was



(a) summer outdoor experiment (b) winter outdoor experiment

Figure 1. Changes in the environmental factors, physical values, and psychological declaration sat on a plastic chair over time.

small, and the change in buttock thermal sensation associated with this was smaller than in summer. Even though buttock clothed temperature and seat surface temperature gradually tended toward an equilibrium temperature, there was no change in the buttock temperature.

We investigate the relationship between seat surface heat flux and buttock thermal sensation using Fechner's law [11] on sensory levels and stimulus levels, as shown in equation (1).

$$E = Klog|S| \tag{1}$$

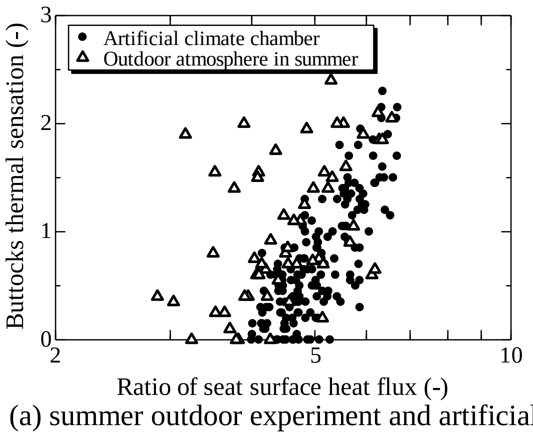
Here, E is the sensory level, S is the stimulus level, and K is a constant. In this study, the sensory level is the buttock thermal sensation, whereas the stimulation level is the seat surface heat flux. We discuss the results obtained from summer outdoor experiments based on equation (1). We saw a correlation in the relationship between the two. The correlation coefficient was R = 0.614. However, the longer is the seating time, the smaller is the seat surface heat flux, and the buttock thermal sensation tended toward the neutral declared value. We left out the stimulus levels that could not be felt by the subjects. We will therefore use Weber's law, which is shown below.

$$\frac{\Delta S}{S} = constant \tag{2}$$

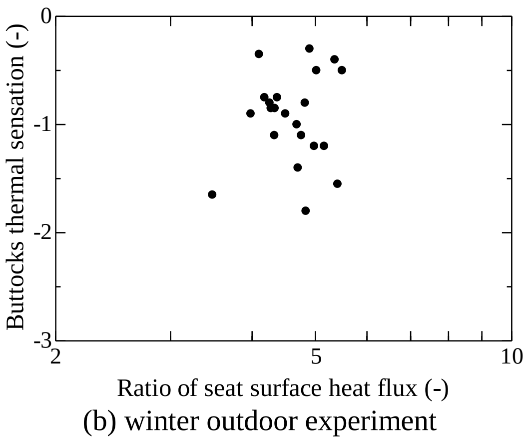
Here, let S be the magnitude of the original stimulus and ΔS be the threshold of the stimulus that can be recognized by humans. We conduct this study to evaluate the local stimulus and the contact thermal sensation. Therefore, thinking that the change in the seat surface heat flux decreases as the seating time increases and is lower than the threshold that humans can recognize, we removed data where the change in the reported buttock thermal sensation is less than 0.2, compared to the sensation reported 3 min earlier. The results obtained thereafter have been shown in Figure 2(a). The seat surface heat flux on the horizontal axis was standardized to 1 W/m^2. We believe that by using Weber's law, we could eliminate data on stimulus levels that could not be recognized by humans.

The experiment was conducted in the artificial climate chamber to maintain uniformity in experimental conditions. Figure 2(a) shows the relationship between the buttock thermal sensation and the seat surface heat flux compared with the results of the summer outdoor experiment. As with the way to process the results of the summer outdoor experiment, we used Weber's law. The data from the artificial climate chamber experiment demonstrated a strong correlation between the seat surface heat flux and the buttock thermal sensation. The correlation coefficient was R = 0.793. While variation is greater in the data measured outside, compared to those measured in the artificial climate chamber, the buttock thermal sensation and the seat surface thermal flux in the two experiments showed almost the same correlation.

Figure 2(b) shows the relationship between the buttock thermal sensation and the seat surface heat flux in the winter outdoor experiment. While the relationship between the seat surface heat flux and



(a) summer outdoor experiment and artificial climate chamber experiment



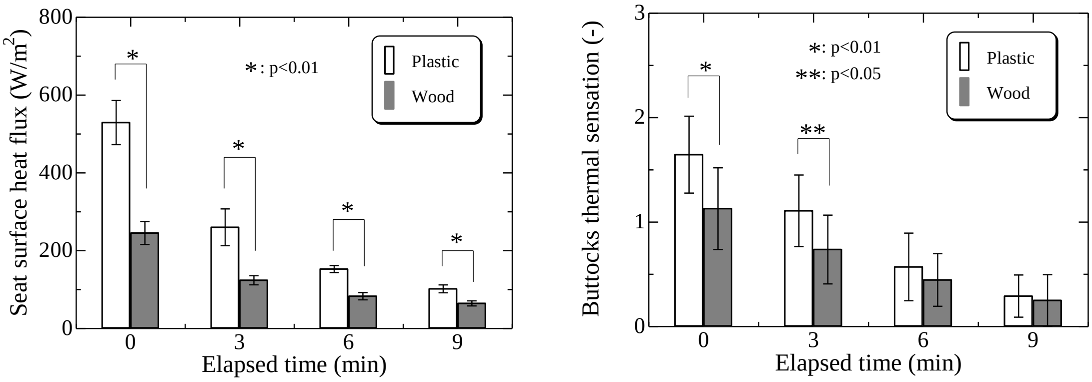
(b) winter outdoor experiment

Figure 2. Correlation between the buttock thermal sensation and the seat surface heat flux.

the buttock thermal sensation shows a negative correlation for cold stimulus, this was not clear. The difference in the contact thermal resistance of clothes can be suggested as a reason for this.

Figure 3(a) and (b) show the results of significance testing on the seat surface heat flux and the buttock thermal sensation when the subjects sat on the plastic and wooden seat surfaces set to 50°C, which were obtained in the artificial climate chamber. The seat surface heat flux was significantly different depending on the type of seating surface; however, the buttock thermal sensation demonstrated that there was no significant difference when the seating time was long.

We examined whether the buttock thermal sensation affects the whole-body thermal sensation. Figure 4 shows the relationship between the whole-body thermal sensation and the buttock thermal sensation. Despite the change in buttock thermal sensation after seating, there was no change in the whole-body thermal sensation, which made it clear that the buttock thermal sensation does not affect the whole-body thermal sensation. The whole-body comfort levels also demonstrated similar trends. The reason for this is that solar radiation is greater than the seat surface heat flux and solar radiation is greater in the area that receives its heat, so it is conceivable that solar radiation is dominant when determining the whole-body thermal sensation and whole-body comfort levels.



(a) Seat surface heat flux (b) Buttock thermal sensation

Figure 3. Difference in seat surface heat flux and buttock thermal sensation according to the seat surface material during the artificial climate chamber experiment (hot stimulus).

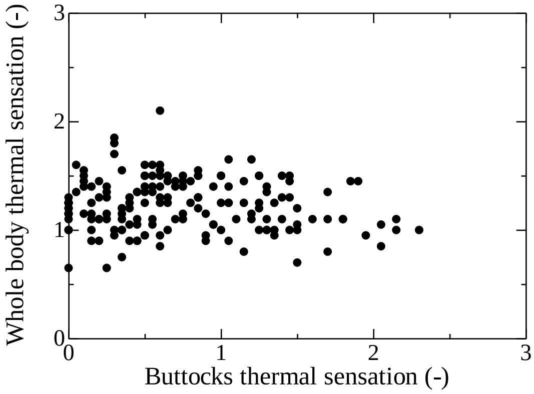


Figure 4. Correlation between whole-body thermal sensation and buttock thermal sensation in the artificial climate chamber experiment.

4. Numerical Calculations

We consider the heat transfer phenomenon when semi-infinite solids with different thermophysical properties come into contact. When the temperatures of the human body and the object material are defined as T_H °C and T_M°C, respectively, the unsteady one-dimensional heat conduction equation describing the thermal diffusion phenomena in each is shown below. The subscripts *H* and *M* represent the physical quantities of human body and object material, respectively.

$$\frac{\partial^2 T_H(t,x)}{\partial x^2} = \frac{C_H \rho_H}{\lambda_H} \frac{\partial T_H(t,x)}{\partial t} \tag{3}$$

$$\frac{\partial^2 T_M(t,x)}{\partial x^2} = \frac{C_M \rho_M}{\lambda_M} \frac{\partial T_M(t,x)}{\partial t} \tag{4}$$

Here, C is the specific heat capacity in J/(kg· K), ρ is the density in kg/m^3 and λ is the thermal conductivity in W/(m· K). Solving equation (3) and (4) by applying the boundary conditions, (a) results in equal heat flux at the contact surface between the human body and the material and (b) constant temperature (initial temperature) at a position sufficiently far away from the contact surface allows us to determine the heat flux $q(t)$ at the contact surface between the human body and the material. The initial temperature is uniform for the human body and the material. If the contact thermal resistance R is 0, then

$$q(t) = \frac{\eta_M}{\sqrt{\pi t}} (T_{iniM} - T_{CS}) = \frac{\eta_M}{\sqrt{\pi t}} \frac{T_{iniM} - T_{iniH}}{1 + \frac{\eta_M}{\eta_H}} \tag{5}$$

where η is thermal effusivity in J/s$^{1/2}$·m^2·°C and T_{CS} represents the contact surface temperature in °C. It is clear that the contact heat flux at the seat surface is dominated by the ratio between the thermal effusivity of seat surface material and thermal effusivity of the human skin.

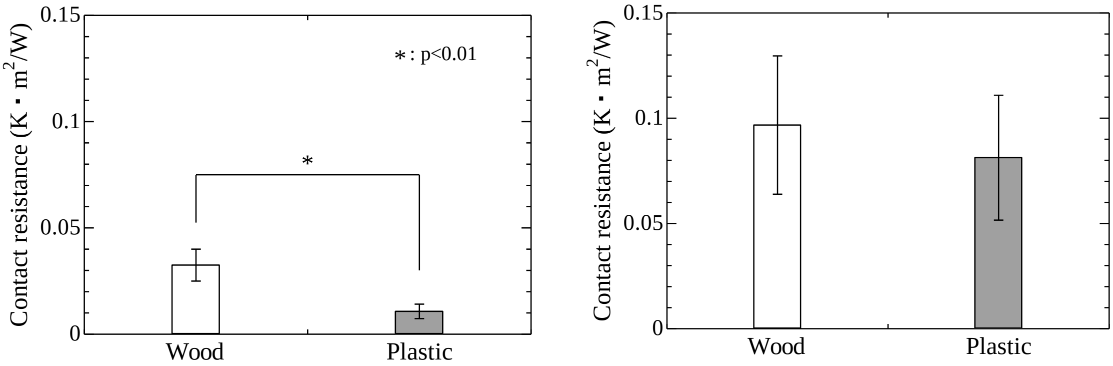
In this experiment, contact thermal resistance due to clothing, etc., was considered non-negligible when the subjects sat on the bench. If there is contact thermal resistance R, a difference arises in the contact surface temperature between the human body and the material. The heat flux at the contact surface, that is the seat surface heat flux, is given as

$$q(t) = \frac{\frac{\eta_H \eta_M}{\sqrt{\pi t}}}{\frac{R \eta_H \eta_M}{\sqrt{\pi t}} + \eta_H + \eta_M} (T_{iniM} - T_{iniH}) \tag{6}$$

The contact thermal resistance at the seat surface is determined by changing the contact thermal resistance R and fitting it to the experimental value of the seat surface heat flux. As representative values of thermal effusivity for the wood (Radiate pine, laminated veneer lumber) and plastic (high density polyethylene) materials used in this study, we used 300 and 600 J/s$^{1/2}$·m^2·°C, respectively. The thermal effusivity of human skin [12] was set to 1590 J/s$^{1/2}$· m^2· °C.

We examined the relationship between the type of seat surface and the contact thermal resistance by comparing the results of the artificial climate chamber and winter experiments. The results are shown in Figure 5(a) and (b). While the hot stimulus significantly varied depending on the type of seat surface, there was no significant difference for the cold stimulus. There was no difference in the contact thermal resistance of the subjects. The clear relation between the buttock thermal sensation and the kind of chair as shown in Figure 3(a) and (b) was influenced by the contact thermal resistance other than the thermophysical properties of chair material for hot stimulus. The fact as shown in Figure 2(b) for cold stimulus is thought to be because of the large contact thermal resistance during the winter compared with the summer, which made it difficult to feel the buttock thermal sensation.

Since buttock thermal sensation correlates strongly with seat surface heat flux, as equation (6) that represents seat surface heat flux shows, it is affected by the thermal effusivity of the seat surface material, seat surface temperature at the time of seating, and the contact thermal resistance between the seat surface and the buttocks. In order to alleviate the buttock thermal sensation, it is desirable to use a material with a low thermal effusivity, such as wood as the seating surface, to have a seating surface with a low solar radiation absorptance, and use a seating surface with large contact thermal resistance.



(a) Artificial climate chamber experiment (hot stimulus)
(b) Winter outdoor experiment (cold stimulus)

Figure 5. Differences in seat surface heat flux due to differences in environmental conditions and seat surface material.

5. Conclusion

(1) Based on the seat surface heat flux, which was considered as the local stimulus, we could predict the contact thermal sensation (buttock thermal sensation). We were unable to clarify the difference in susceptibilities of the buttock thermal sensations to hot and cold stimuli.

(2) We calculated the seat surface heat flux using the thermophysical properties of the seating surface material and the contact thermal resistance between the seat surface and human buttock and demonstrated that it was possible to predict the buttock thermal sensation.

(3) In the outdoor environment, we can neglect the effect of buttock local stimulation on whole-body thermal sensation and comfort.

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