Academic Article

Measurement of physiological responses of walking and standing pedestrians exposed to changeable thermal environment in outdoor space

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ABSTRACT

In recent years, health hazards during extremely hot summer conditions have increased rapidly with urban heat islands, severe weather, etc. Previous studies have employed thermal comfort or thermal stress indices, such as SET*, PET, WBGT, etc., to assess outdoor thermal environment, and the health hazard risk is considered to be very high at the points where such indices are higher than the threshold values. However, people in outdoor spaces often walk in real-life situations on urban streets, and do not stay in the same place for prolonged periods of time. Thus, even when there are extremely hot points in the evaluation area, the health risk may not be high if there are also cool spots nearby. This study simultaneously measured outdoor thermal environments and human physiological responses to determine the effects of changeable environments (e.g, wind velocity and radiation) on pedestrians walking and standing in outdoor spaces.

Field measurements were performed in pedestrian spaces within the premises of Tohoku University from September 26-30, 2014. The subject wore clothes with instruments attached to measure physiological variables (skin surface temperature, core temperature, heat flux at skin surface and blood pressure) and they walked with a cart with attached instruments for meteorological variables (air temperature, relative humidity, globe temperature, wind velocity, and short- and long-wave radiation). In this study, five sets of measurements were carried out to evaluate the influence of four characteristics of the outdoor environment that are not usually found in indoor environments:

(1) wide ranges of wind velocity,
(2) wide ranges of radiation,
(3) sudden change in the surrounding environment (mostly due to moving to other places) and
(4) physiological changes induced by walking.

The results obtained from these measurements were as follows.

(1) When mean wind velocity changed from approx. 0 m/s to 1.4 m/s, skin temperature decreased gradually.
(2) When MRT changed from 20°C to 75°C, skin temperature increased rapidly even though mean wind velocity was 1.2 m/s.
(3) When environmental condition, especially MRT, changed suddenly, skin temperatures varied greatly at the body parts covered without any clothes.
(4) Skin temperature during walking was lower than that during standing.

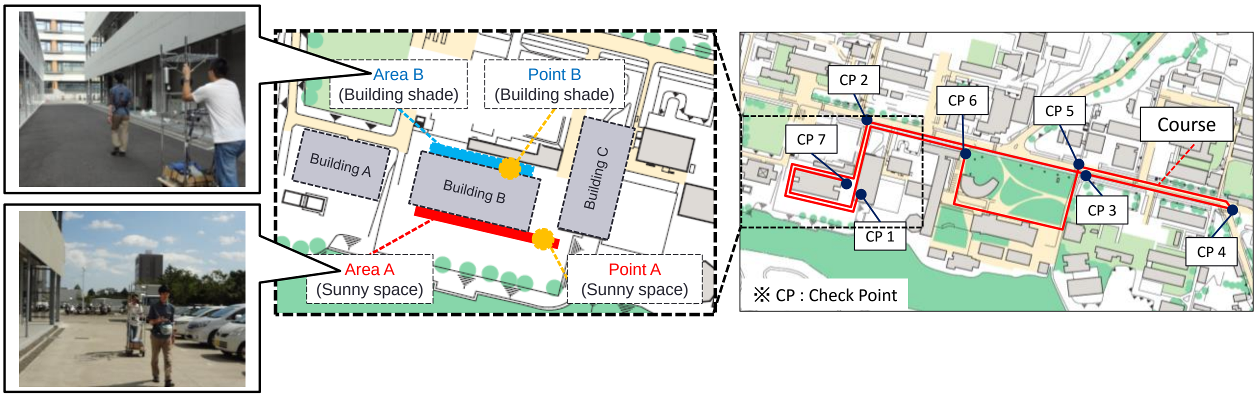
Key Words : Walking pedestrians, Moving measurements of outdoor thermal environment, Human physiological responses

1. Introduction

In recent years, health hazards in extremely hot summer conditions have increased rapidly with urban heat islands, severe weather, etc. Previous studies employed thermal comfort or thermal stress indices, such as SET*[(1)], PET[(2)-(4)], WBGT[(5)], etc. to assess the outdoor thermal environment[(6)-(10)], and the health hazard risk is considered to be very high at the points where such indices are higher than the threshold values. However, people in outdoor spaces are often walking on urban streets, and they do not stay at the same point for a long time.

Thus, even though there are very hot points in the evaluation area, health risks are not high if there are cool spots nearby. For this study, simultaneous measurements were performed of outdoor thermal environments and physiological responses of pedestrians walking and standing in outdoor spaces in order to determine the effects of changeable environment factors in outdoor spaces (e.g, wide ranges of wind velocity and radiation) on pedestrians.

2. Field measurements of outdoor thermal environment and pysiological responses

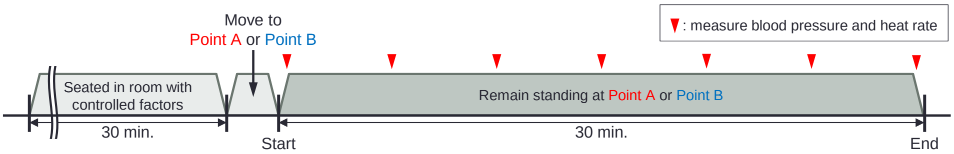


(1) Each Area or Point name (2) Course for Case 5

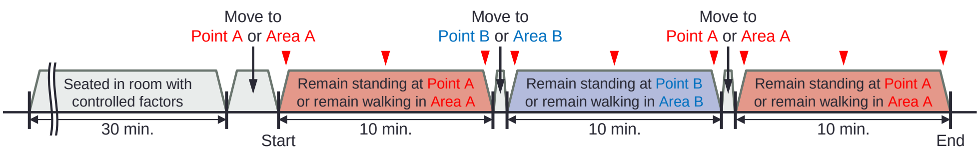
Fig. 1: Measurement Areas.

Table 1: Schedules and Factors Considered in Each Case.

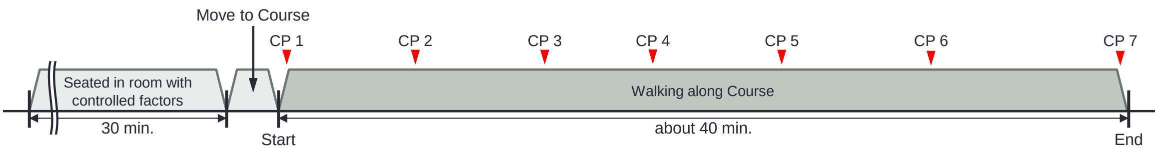
	Schedule	Factors Considered
Case1	Remain standing at Point B (Building shade, Fig. 1 (1)) for 30 min.	Wide ranges of wind velocity
Case2	Remain standing at Point A (Sunny space, Fig. 1 (1)) for 30 min.	Wide ranges of wind velocity + Wide ranges of radiation
Case3	Moving from Point A to Point B and Point B to Point A (Fig. 1 (1)), and remain standing for 10 min. at each point.	Wide ranges of wind velocity, Wide ranges of radiation + Rapid chang of surrounding environment
Case4	Moving from Area A to Area B and Area B to Area A (Fig. 1 (1)), and remain walking for 10 min. in each area.	Wide ranges of wind velocity, Wide ranges of radiation, Rapid chang of surrounding environment, + Walking
Case5	Walking along Course (Fig. 1 (2)).	Walking along real outdoor space



(1) Cases 1 and 2



(2) Cases 3 and 4

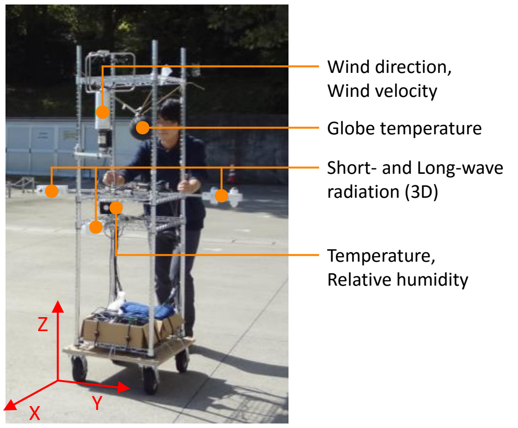


(3) Case 5

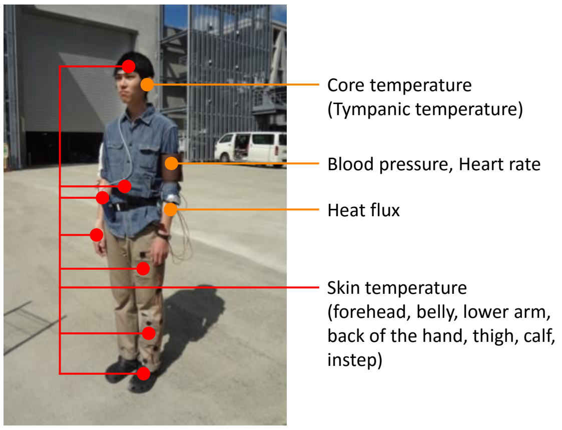
Fig. 2: Case Schedules.

Table 2: Measured Meteorological and Physiological Variables and Instruments Used.

Variables	Instruments	Interval	Height
Wind direction, wind velocity	3D ultrasonic anemometer (R.M. Young, CYG-81000)	0.1 s	1.8 m
Air temperature, relative humidity	Thermistor/polymer sensors (T&D,TR-72U) with double blower pipe and sun shield	1 s	1.0 m
Globe temperature	Globe ball with thermocouple	1 s	1.5 m
Short- and long-wave radiation	Net radiometer (EKO, MR-60)	1 s	1.0 m
Skin temperature	Thermocouple (forehead, belly, lower arm, back of the hand, thigh, calf and instep)	1 s	
Core temperature (tympanic temperature)	Thermopile and thermistor (TECHNO SCIENCE, BL-100)	1 s	
Heat flux (lower arm)	Heat flux sensor (CAPTEC, HF-D30)	1 s	
Blood pressure (upper arm), heart rate	Blood pressure monitor (A&D, TM-2431)		
Evaporated sweat	Digital weight scale (A&D, GP-100K)		
Positional information	Mobile phone		



(1) Cart for measurement of meteorological variables



(2) Clothing for measurement of physiological variables

Fig. 3: Cart and Clothing with Attached Instruments.

2.1 Case Settings

Field measurements were carried out in the open space within the premises of Tohoku University from September 26-30, 2014. The measurement areas are shown in Fig. 1. The measurement start times were 12:35 on 26th in Case 1, 10:40 on 26th in Case 2, 10:35 on 28th in Case 3, 12:35 on 28th in Case 4 and 10:33 on 30th in Case 5, respectively.

In this study, four factors were identified that affect human physiological responses in outdoor spaces:(1) wide ranges of wind velocity, (2) wide ranges of radiation, (3) rapid changes in the surrounding environment (mainly caused by moving to other places) and (4) walking. Five types of measurements were performed to determine how these factors affected pedestrians. The schedules and factors considered in each case are shown in Table1 and Fig. 2. In Cases 1 to 4, the factors considered were added one at a time in order to assess human physiological responses to each factor, while the physiological responses of pedestrians walking in real outdoor space were measured in Case 5. In Case 2 and Case 3, the subject stood at Point A with the front of the body facing in the direction of the sun. Subject remained sitting for 30 min in a controlled room in Building B, where air temperature was 24 °C, relative humidity was 42 %, indoor airflow velocity was approximately 0 m/s, mean radiant temperature (MRT) was 24 °C and all the meteorological factors were held constant, before each measurement.

2.2 Measured Variables

The measured variables are shown in Table 2. A cart with attached instruments was used to measure meteorological variables, including relative wind direction and relative wind velocity (absolute value of the difference between the wind velocity in the area and the moving velocity of the cart), temperature, relative humidity, short-wave radiation and long-wave radiation, and globe temperature. Three net radiometers were used to measure three-dimensional (3D) radiant heat transports. This enabled us to evaluate short- and long-wave radiant heat fluxes from the front, back, right, left, top, and bottom.

Clothing with attached instruments was used to measure physiological variables, including skin temperature, core temperature (tympanic temperature), heat flux at the skin surface of the arm, blood pressure, and heart rate. Heat resistance value by clothes was 0.65 clo. Blood pressure and heart rate were measured as follows (Table 1): every five minutes for Cases 1 and 2, just after (and before) leaving area, five minutes before leaving the area in Cases 3 and 4, and when the subject reached each check point (CP 1~7 in Fig. 1) in Case 5. The subject remained standing for approximately one minute while measuring blood pressure and heart rate even in Cases 4 and 5. The cart and clothing are shown in Fig. 3. Weight was measured at the beginning and end of each measurement and evaporated sweat was assumed to be their difference. Positional information was measured using a global positioning system (GPS) with a mobile phone and the walking speed was kept 1.1 m/s in Case 4 and Case 5.

Fig. 3 (2) shows a subject in this measurement. The subject was a man with age 23, height 1.78 m and weight 60 kg.

SET* at each time was calculated by using mean skin temperature and core temperature computed from iterative calculation by 2-node model[1] using measured air temperature, relative humidity, wind velocity and MRT at each time as input data. This method was developed by Nakamura et al.[11]

3. Results of Field Measurement

3.1 Case 1 (Standing in building shade)

Fig. 4 (6) shows the time variations of skin temperatures of various parts of body in Case 1. When mean wind velocity changed from approx. 0 m/s in the controlled room to 1.4 m/s, the skin temperatures of all parts decreased as time proceeded, although the rate of change was diverse. Fig. 4 (9) shows the heat flux at skin surface in Cases 1 and 2. Here, the positive sign means the heat flux incoming to the skin surface. The heat flux outgoing from the skin surface moderately decreased between 5 and 30 minutes after measurement started in Case1. It is probably because the convective heat transfer was suppressed by the decrease in skin temperature.

Mean skin surface temperature was calculated from seven skin surface temperatures (the forehead, the belly, the lower arm, the back of the hand, the thigh, the calf and the instep) by weighted averaging based on the seven-point method developed by Hardy and DuBois[12].

Fig.4 (8) shows that mean skin temperatures decreased gradually in building shade in Case 1. In the controlled room environment, meteorological variables were almost equal to those measured at Point B except the wind velocity, and mean skin temperature was kept constant; therefore, we concluded that the decrease in the skin temperature was caused by the wide ranges of wind velocity in the outdoor space.

3.2 Case 2 (Standing in a sunny space)

Figs. 4 (1),(2),(3) and (4) show that the meteorological variables in Case 2 were almost the same as those measured in Case 1, except MRT. The tendency of the time variation of SET* was similar to that of MRT, as shown in Figs. 4 (4) and (5). Figs. 4 (4),(7),(8) and (9) show that heat flux became positive (surface of the skin gained heat) and skin temperatures increased in Case 2 when MRT was high; 0-8 and 18-24 minutes after measurement started.

Fig. 4 (7) presents that the tendency of each skin tempareture change varied depending on the body part. When MRT changed from 20 °C in the room to 75 °C, the skin temperatures increased rapidly even though mean wind velocity was 1.2 m/s. Especially, the amount of rise in temperatures of forehead and back of the hand were large. These results show that the skin temperature fluctuation was large at the parts not covered with clothing where thermal resistance by clothes was low or zero.

Blood pressure showed little change, and the values in Case 1 and Case 2 were almost the same, as shown in Fig. 4 (10). Fig. 4 (11) shows that heart rate in Case 2 was consistently higher than Case 1. It is inferred that heart rate increased to increase blood flow due to heat release from the body.

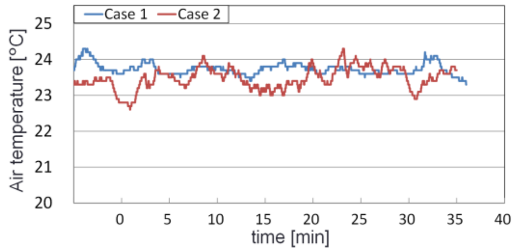
3.3 Case 3 (Alternately standing in sunny space and building shade)

Results of Cases 3 and 4 are shown in Fig. 5. Skin temperatures increased in sunny spaces and decreased in building shade, as shown in Figs. 5 (6), (7) and (8). Similarly to the results of Case2 mentioned in Section 3.2, a clear relationship was observed between the skin temperature and thermal resistance by clothes.

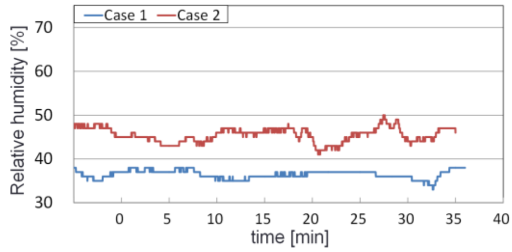
3.4 Case 4 (Alternately walking in sunny spaces and building shade)

Skin temperatures increased in sunny spaces and decreased in building shade, as shown in Figs. 5 (7) and (8). However, the range of the increase in Case 4 (walking) was smaller than that of Case 3 (standing) for the following reasons: latent heat release by evaporation of sweat and partial increase of relative wind velocity from the arms and legs while walking. In Case 4, the metabolic rate and the relative wind velocity were higher than those in Case 3, therefore, there was no obvious difference in SET* between the two cases. Fig. 5 (9) shows that heat flux in sunny spaces also changed intricately in Case 4. It is inferred that heat flux was positive because the heat flow plate attached to the left lower arm was exposed to solar radiation when the subject walked from east to west, while that flux became negative because the left arm fell into the shadow of body when the subject walked from west to east. Moreover, the absolute value of heat flux in Case 4 when the subject walked from east to west was smaller than that in Case 3. This is considered partly due to increase in convective heat transfer by arm swinging while walking.

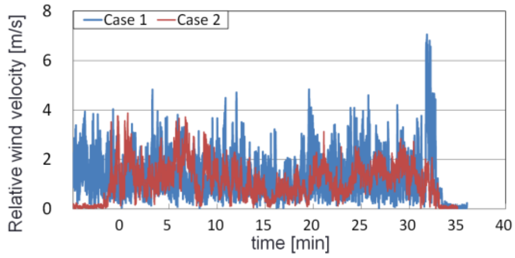
Fig. 5 (10) shows that blood pressure in Case 3 and Case 4 were almost the same and constant. The tendency that the heart rate in sunny space became higher than that in the building shade was the same in both Case 3 and Case 4, although the value of Case 4 was overall lower than that of Case 3, as shown in Fig. 5 (11). Under this experimental condition, no increase in heart rate caused by an increase in metabolic rate was measured.



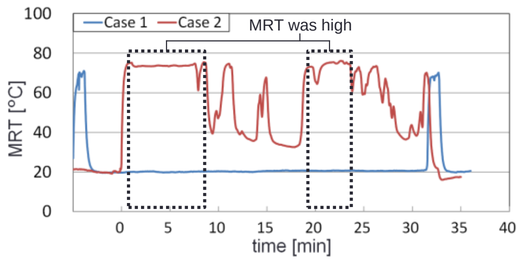
(1) Air temperature



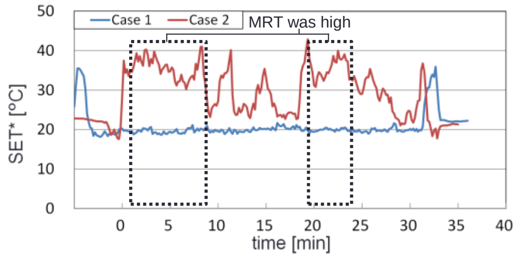
(2) Relative humidity



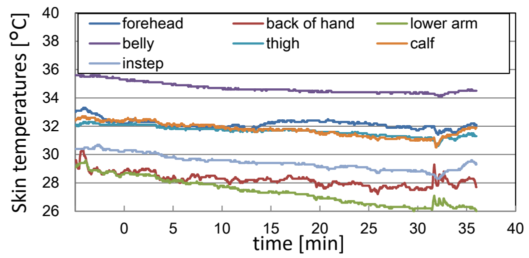
(3) Relative wind velocity



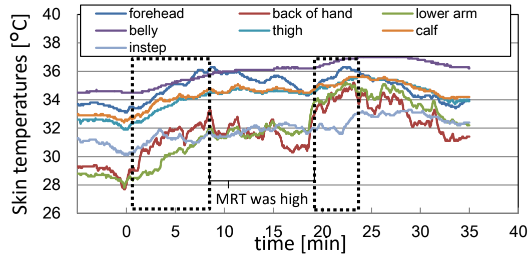
(4) MRT



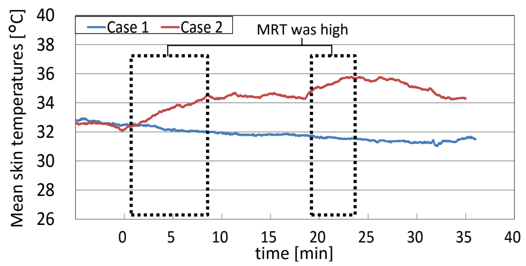
(5) SET*



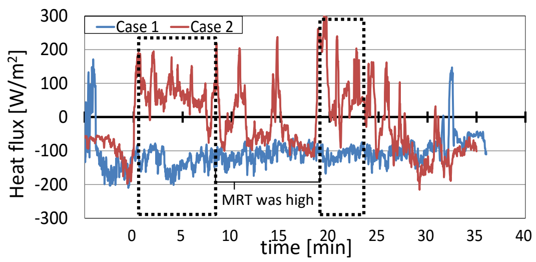
(6) Skin temperatures of Case 1



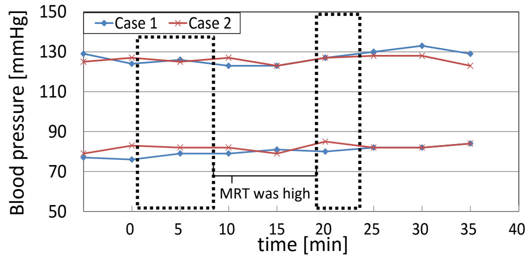
(7) Skin temperatures of Case 2



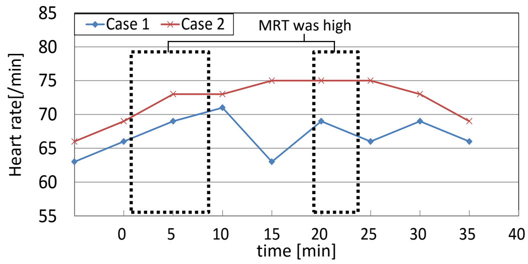
(8) Mean skin temperature



(9) Heat flux at skin surface

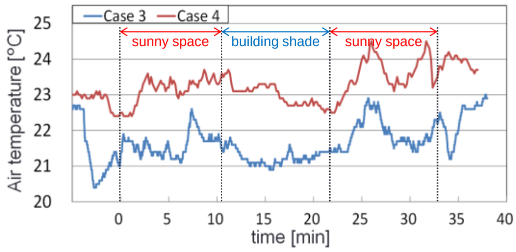


(10) Systolic blood pressure and diastolic blood pressure

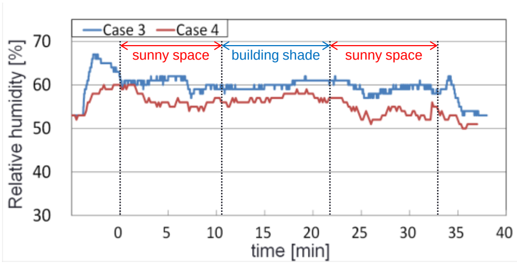


(11) Heart rate

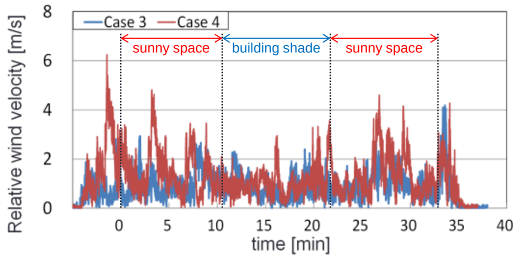
Fig. 4: Results of Case 1 (standing in building shade) and Case 2 (standing in a sunny space).



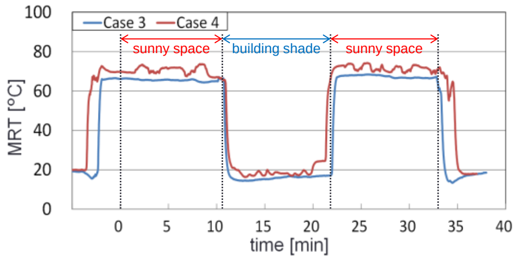
(1) Air temperature



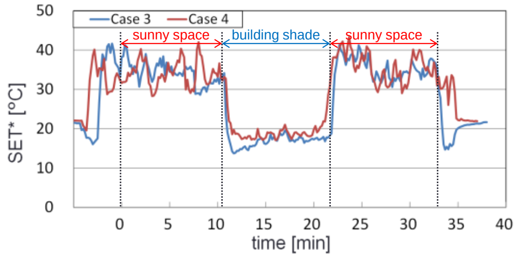
(2) Relative humidity



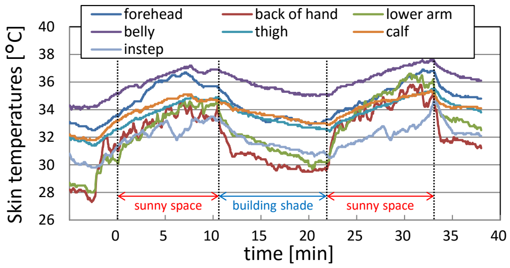
(3) Relative wind velocity



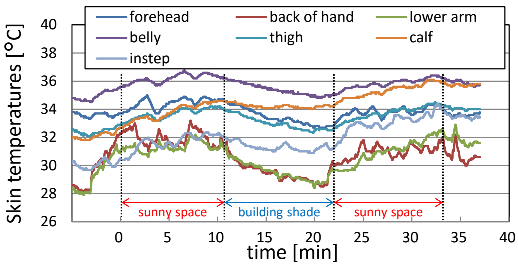
(4) MRT



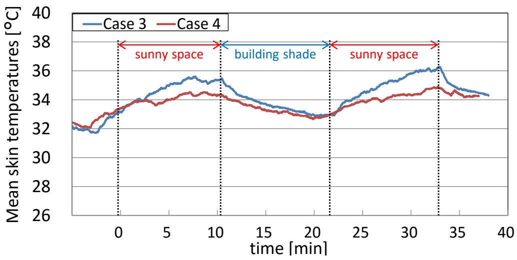
(5) SET*



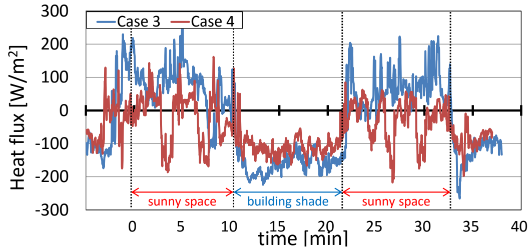
(6) Skin temperatures of Case 3



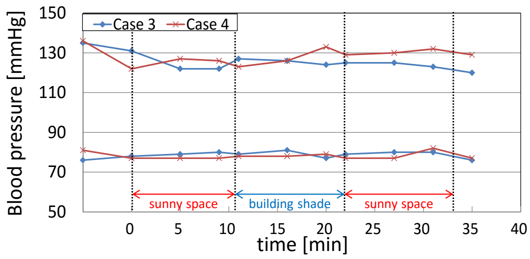
(7) Skin temperatures of Case 4



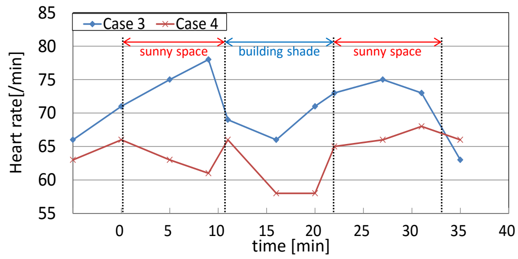
(8) Mean skin temperature



(9) Heat flux at skin surface

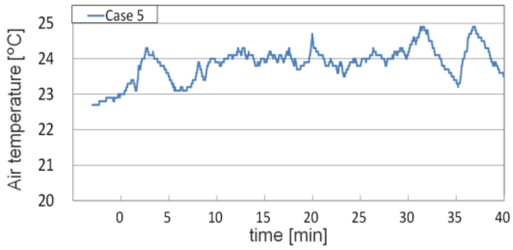


(10) Systolic blood pressure and diastolic blood pressure

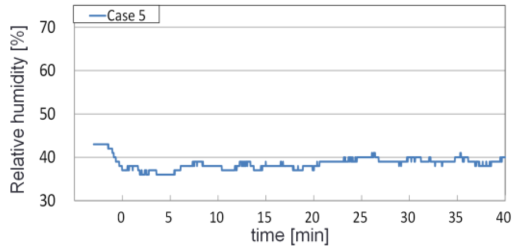


(11) Heart rate

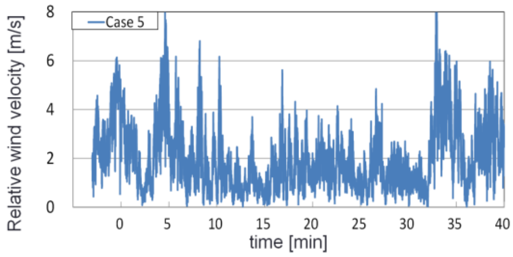
Fig. 5: Results of Case 3 (alternately standing in sunny spaces and building shade) and Case 4 (alternately waking in sunny spaces and building shade).



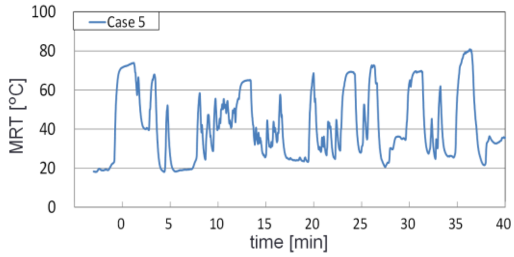
(1) Air temperature



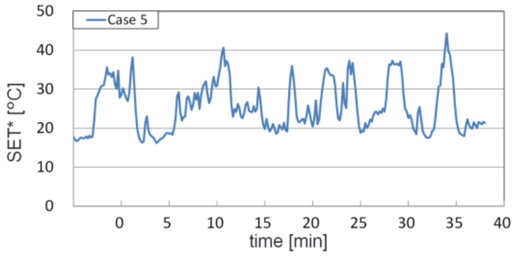
(2) Relative humidity



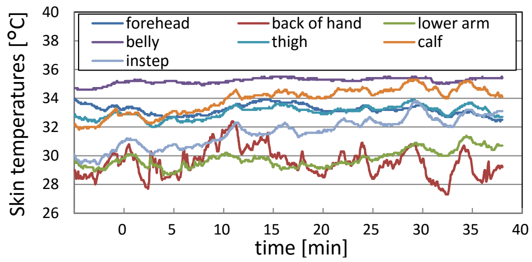
(3) Relative wind velocity



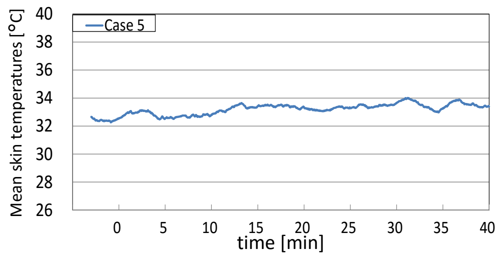
(4) MRT



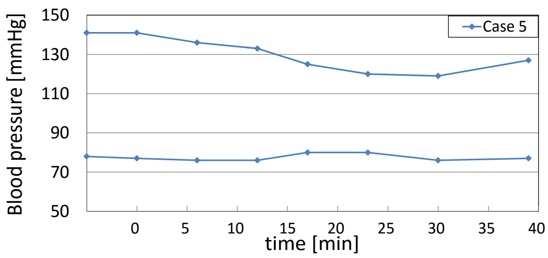
(5) SET*



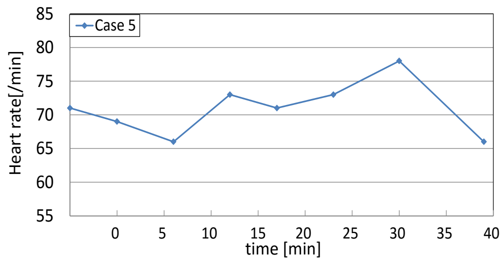
(6) Skin temperatures of Case 5



(7) Mean skin temperature



(8) Systolic blood pressure and diastolic blood pressure



(9) Heart rate

Fig. 6: Results of Case 5 (walking along a course).

3.5 Case 5 (Walking along a course)

Fig. 6 summarises the results of Case 5, walking along a course. Fig. 6 (6) presents that only the skin tempareture of the back of the hand changed intricately while that of other parts had small change. The range of variation in mean skin temperature was smaller in Case 5 than in other Cases, as shown in Fig. 6 (7). This was likely because the subject was exposed to a very unsteady environment and did not remain in a hot or cold environment for prolonged periods of time. However, only the skin tempareture of the back of the hand had a high response to the thermal environment.

The diastolic blood pressure was maintained almost constant while the systolic blood pressure decreased as time passed, as shown in Fig. 6 (8).

3.6 Amount of evaporated sweat

Table 3 shows the amount of evaporated sweat of each Case. Comparing Case 1 and Case 2 conducted on the same day, the amount of evaporated sweat increased due to solar radiation. The more sweating occurred by walking in Case 4 compared with Case 3.

Table 3: Amount of Evaporated sweat

Case	Evaporated sweat	Date
1	36 g	26 th
2	191 g	26 th
3	15 g	28 th
4	46 g	28 th
5	55 g	30 th

4. Conclusions

(1) Simultaneous measurements of outdoor thermal environments and human physiological responses were performed to determine how changeable environmental conditions in outdoor space affected pedestrians.

(2) The results of these measurements were as follows.

(a) When mean wind velocity changed from approx. 0 m/s to 1.4 m/s, skin temperature decreased gradually.

(b) When MRT changed from 20 °C to 75 °C, skin temperature increased rapidly even though mean wind velocity was 1.2 m/s.

(c) When environmental condition, especially MRT, changed suddenly, skin temperatures varied greatly at the body parts covered without any clothes.

(d) Skin temperature during walking was lower than that during standing.

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