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Translated Paper

Effect of ventilated workwear and working schedule on physiological and psychological responses of construction workers, no. 2: Actual investigation at an active construction site

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Abstract

Although the use of cooling garments to prevent heat disorders has been increasing, the effectiveness of such garments at construction sites (CSs) remains underexplored. We investigated the relationship between the thermal environment at a CS and the physiological and psychological responses of workers wearing/not wearing ventilated work wear (VWW). The study participants were rebar placers and form workers employed at an outdoor CS. The thermal environmental conditions and the physiological and psychological responses of the workers were measured. The overall, chest, and forearm skin temperatures of the workers not wearing VWW were significantly higher than those of workers wearing VWW. To clarify the effects of VWW and working schedules on body weight loss (BWL), the BWL rate was simulated based on the evaporation rate according to a regression formula of measured data in an artificial chamber. The BWL during the late shift was higher than that in the early shift, causing dehydration in the afternoon. To prevent this condition, more water intake is required during the late shift.

Keywords

construction worker, rate of body weight loss, skin temperature, ventilated workwear, working schedule

1. Introduction

In recent years, the use of cooling garments as a measure against heat disorders has been increasing. There are several types of cooling garments, such as cooling vests with ice packs[1] and/or phase change materials (PCMs),[2] and forced-ventilated cooling garments.[3] The effectiveness of cooling garments has been verified mainly using human participants and thermal manikins[4] in artificial chambers (AC). The use of ventilated work wear (VWW) with superior lightweight material and sustainability is rapidly expanding at construction sites (CSs). Chan et al[5] developed a hybrid cooling vest that combines a PCM and multiple fans and verified its effectiveness at CSs. However, little research has been conducted on the effectiveness of cooling garments at CSs.

In a previous study, the authors evaluated the effects of factors such as VWW and working schedule (WS) on the physiological and psychological responses of construction workers (CWs) (indoors: interior workers/plumbers; outdoors: rebar) at CSs in Tokyo from July to August 2016.[6] Although the effect of VWW was identified in the psychological response, its effect on the physiological response was established only in four parameters (outdoors: mean skin temperature (MST), inner ear temperature, walking, indoors: board and plumbing work). Although the outdoor mean radiant temperature was significantly lower in the afternoon than in the morning, the

MST of outdoor CWs was found to be significantly higher in the afternoon than in the morning. Therefore, it was considered that the increase in thermal sensation of the form workers (FWs) in the afternoon as identified by the path analysis was not due to the thermal environment. Because the sweat rate was not measured, the authors could not evaluate the effect of dehydration on thermal sensation.

To evaluate the effect of VWW under controlled conditions in terms of temperature, activity, and clothing, the authors conducted an experiment with human participants using an AC from May to June 2017.[7] In an environment (air temperatures of 29 and 34°C and relative humidity of 50%) simulating a CS, the study participants (rebar placers (RPs) and FWs) performed simulated work, and their physiological and psychological responses when wearing/not wearing VWW were measured. The amounts of naked and clothed body weight loss (BWL) were measured, and the sweat content of their clothing (SCC) was calculated from the difference between the two. The results revealed that at 34°C, wearing VWW reduced the average skin temperature by approximately 0.4°C and the sublingual temperature by approximately 0.1°C. Moreover wearing VWW showed significantly lower values of SCC and heart rate (HR). No significant difference was observed in the rate of clothed BWL, which indicates the rates of evaporated sweat and insensible perspiration. Based on these results, a significant path model was created stating that "the SCC significantly changes, and the HR increases or decreases depending on the air temperature and whether VWW is worn." However, since the environment inside the AC is constant and the activity is less intense than that at an actual CS, it is necessary to measure the weight loss at actual CSs and verify the effectiveness of VWW.

Therefore, the present study aims to verify the effect of VWW, which was confirmed in the AC experiment, on the MST and local skin temperature at an actual CS. In particular, weight loss, which was not measured at the CS in the previous report,[6] is measured, and the effects of factors, namely VWW and WS on weight loss are examined. We verify in detail whether thermal stress and dehydration of workers depend on the WS at the CS, which is a problem presented in the previous study.[6] The study findings are expected to contribute toward improving the drinking frequency and WS of CWs.

Since the publication of the Japanese version of this paper, we have been conducting research regarding the effectiveness of VWW. Yamazaki et al analyzed the data obtained in this study in more detail and reported it in a Japanese version of the paper.[8] The analysis demonstrated that there is a limit to the amount of water that workers at a CS can drink, and it was verified that, in the CS setting, the BWL increased with increasing wet bulb globe temperature mainly due to insufficient rate of water intake (RWI). The findings suggested that BWL could be partly decreased by using VWW, which decrease the sweat rate.

2. Methods

2.1 Measurements and location

2.1.1 Measurement location, schedule, and participants

Table 1 presents the measurement location and schedule. The experiment was conducted at an eight-story reinforced concrete CS in Tokyo for 5 days, from August 3 to 8, 2017. The participants were four FWs, three RPs, two earth workers, and one scaffold worker employed at an outdoor CS. Figure 1 shows the working conditions of the RPs and FWs. As indicated in Figure 1A, the FWs were engaged in the construction of the column and beam formworks on the sixth floor, and in Figure 1B, the RPs were engaged in the arrangement of the beam on the ground. Table 2 summarizes the age, height, and weight of the 10 healthy male participants. Five participants wore VWW each day, whereas the remaining five did not. Except for the scaffold worker, it was possible to set the conditions for both wearing and not wearing VWW in each occupation on the same day. Thereafter, the wearing and non-wearing days were arranged alternately.

This study was conducted with the approval of the Medical Research Ethics Review Committee for Humans of Iwate University (No. 201703, June 19, 2007). Prior to the experiment, the participants were provided a detailed explanation, and verbal and written consents were obtained.

2.1.2 Thermal environment and physiological and psychological responses

Table 3 lists the instruments used for measuring the thermal environment and physiological responses of the human body. The measurement interval was 1 minute for both environmental and human body measurements. The measuring equipment for the thermal environment was installed at the end of the work area on the ground where the RPs mainly work and at the center of the work area on the sixth floor where the FWs mainly work (Figure 2).

The air temperature and relative humidity 1 point (1.5 m above the floor), wind speed (1 hot wire type, 3 cups type 1 point [2 m]) and gray globe temperature 1 point (1 m) were measured, and a temperature and humidity sensor was fixed inside a small natural ventilation shelter to prevent thermal radiation to the sensor. At the sixth floor measurement point, the solar radiation on the horizontal plane was measured using a pyranometer located at 1.5 m above the floor. At the ground measurement point, the solar radiation reaching the globe thermometer was measured from the black and white globe thermometers positioned at 1 m above the floor.

The measurement point on the sixth floor was a well-ventilated place for the first 3 days, but after the second day, surrounding walls were built, and for the final 2 days, the measurement point was poorly ventilated.

Before starting work in the morning, the participants wore an electrocardiograph (chest band), button-type thermometer (4 points: forearm, chest, thigh, and lower leg skin), wristband type life recorder (left wrist),[6] and HR monitor (right wrist). Work at the construction site was generally performed from 08:00 to 17:00, and this was divided into four periods with breaks (AM1: 8:00 to 10:00, AM2: 10:30 to 12:00, PM1: 13:00 to 15:00, and PM2: 15:30 to 17:00). The clothed body weight, water intake, sublingual temperature, and sensation votes were entered eight times before and after each WS. The water intake was recorded as the reduction in sports drinks during WS [Note 1]. The MST was calculated as follows: chest skin temperature × 0.3 + forearm skin temperature × 0.3 + thigh skin temperature × 0.2 + lower leg skin

Table 1. Schedule and place

Schedule	August 3, 4, 5, 7, and 8, 2017
Place	Shin-ogawacho, Shinjuku-ku, Tokyo RC, 8F, building construction field

A Form worker B Rebar placer

Figure 1. Working condition of each construction worker. (A) Form worker. (B) Rebar placer

Table 2. Human participants

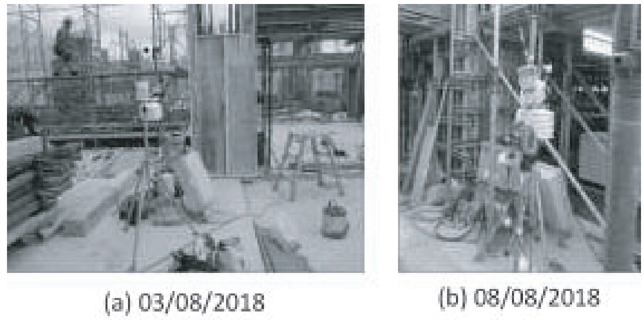
No.	Age	Height (m)	Weight (kg)	Type of occupation
A	68	1.68	66	Form worker
B	51	1.70	62	Form worker
C	20	1.60	49	Form worker
D	50	1.70	82	Form worker
E	32	1.72	73	Earth worker
O	66	1.76	72	Rebar placer
P	24	1.70	51	Rebar placer
Q	28	1.68	66	Rebar placer
R	30	1.72	79	Scaffold worker
S	16	1.68	84	Earth worker

Table 3. Measuring instruments

Electrocardiogram	WHS-1 (Union Tool Corp.)
Skin temperature	Thermoclon SL (KN Laboratory)
Metabolic equivalent of task (MET)	Life recorder (A & D Corp.)
Pulse rate	A360 (Polar Electro)
Sublingual temperature	Electronic thermometer (Terumo Corp.)
Weight, water intake	GP-100K (T&D Corp.)
Air temperature	TR-72 (T&D Corp.)
Relative humidity	
Wind velocity	6533 (Kanomax Japan Inc.)
	200-WS01B (Field Pro)
Solar radiation	SP-110 (Apogee Inst.)
Globe temperature	150mmφ: black and white (Sibata Scientific Technology LTD.)
	40mmφ: Gray (Handmade)

temperature × 0.2. The participants logged their sensation votes by filling out a declaration paper including ratings for thermal, comfort, and thirst sensations (Table 4) [Note 2].

For the analysis, the authors used the data of only four FWs (A, B, C, and D) and three RPs (O, P, and Q) because the work time of scaffold worker R was significantly different from those of other occupations, and the workplaces of earth-workers E and O were often indoors. The wearing and non-wearing days of the FWs and RPs are presented in Table 5. The data of 18 workers wearing VWW and 17 workers not wearing VWW were used for analysis. The average value of each work time (AM1, AM2, PM1, and PM2) was calculated as the thermal environment.



A On the sixth floor for form workers

B On the ground for rebar placer

Figure 2. Equipment for measuring thermal environment. (A) On the sixth floor for form workers. (B) On the ground for rebar placer

Table 4. Sensations

	Thermal sensation	Comfort sensation	Thirst sensation
3	Very hot	Very uncomfortable	Very thirsty
2	Hot	Uncomfortable	Thirsty
1	Slightly hot	Slightly uncomfortable	Slightly thirsty
0	Neutral	Neutral	Not thirsty
−1	Slightly cold	Slightly comfortable	
−2	Cold	Comfortable	
−3	Very cold	Very comfortable	

Table 5. Schedule of participants with and without VWW

	8/3	8/4	8/5	8/7	8/8
With VWW	A, B O, P	C, D Q	A, B O, P	C, D Q	A, B O, P
Without VWW	C, D Q	A, B O, P	C, D Q	A, B O, P	C, D Q

2.2 Analysis

The environmental globe temperature (EGT) and solar radiation incident on the human body were calculated from the black and white globe temperatures.[9] The EGT is defined as the globe temperature considering the effects of air

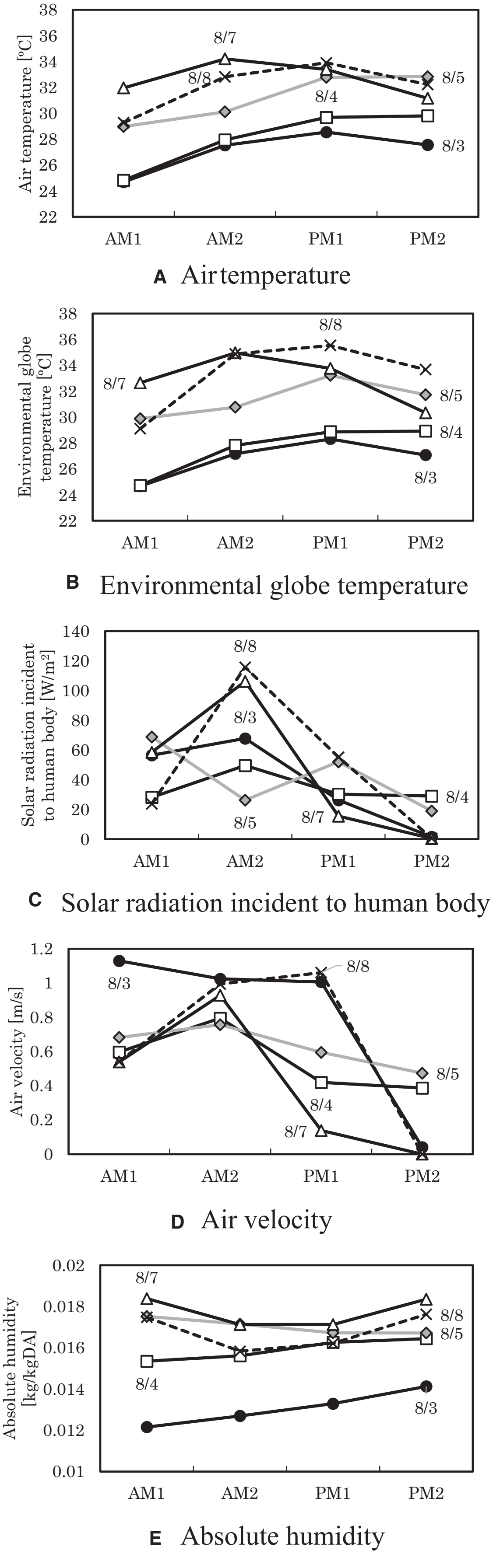


Figure 3. Thermal environment at construction site. (A) Air temperature. (B) Environmental globe temperature. (C) Solar radiation incident to human body. (D) Air velocity. (E) Absolute humidity

temperature and long-wavelength radiation as indicated in Equation (1). The solar radiation incident on the human body is calculated from Equation (2).

$$t_{gle} = \frac{\alpha_b t_{gl,w} - \alpha_w t_{gl,b}}{\alpha_b - \alpha_w} \tag{1}$$

$$I_{sun,gl} = \frac{\left(t_{gl,b} - t_{gle}\right) h_{gl}}{\alpha_b} \tag{2}$$

where t_{gle} is the EGT [°C]; $t_{gl,b}$ and $t_{gl,w}$ are the black and white globe temperatures [°C], respectively; α_b and α_w are the solar absorptance values of the black (0.96) and white (0.21) globe thermometers, respectively; $I_{sun,gl}$ is the solar radiation incident on the human body [W/m^2]; and h_{gl} is the overall heat transfer coefficient of the globe thermometer [W/(m^2·K)].

The evaporation rate (ER) [g/(m^2·h)] was calculated from Equation (3) by using the surface area of the human body, work time, and clothed BWL during work and water intake. The clothed BWL also includes the amount of urine. The rate of water intake (RWI in g/(m^2·h)) in each work time was similarly obtained from Equation (4).

$$\mathrm{ER} = \frac{\text{Clothed BWL}\,[g] + \text{water intake}\,[g]}{\text{Body surface area}\,[\mathrm{m}^2] \times \left(\frac{\text{work time}\,[\mathrm{min}]}{60}\right)} \tag{3}$$

$$\mathrm{RWI} = \frac{\text{Water intake}\,[g]}{\text{Body surface area}\,[\mathrm{m}^2] \times \left(\frac{\text{work time}\,[\mathrm{min}]}{60}\right)} \tag{4}$$

A two-way ANOVA was performed with WS and wearing/not wearing VWW as independent variables and physiological responses (ER, sublingual temperature, MST, and HR) as dependent variables. Data for 140 workers, namely 3 RPs (4 times/day × 3 workers × 5 days = 60 workers) and 4 FWs (4 times/day × 4 workers × 5 days = 80 workers), were analyzed. However, the data of 2 FWs were excluded due to a failure in the measuring equipment; therefore, the effective analysis target was 138 participants, i.e., 60 RPs and 78 FWs. However, the data of 15 FWs and 14 RPs were excluded due to electrocardiograph (chest bands) failure; thus, the effective analysis target of electrocardiographs was 111 participants, consisting of 46 RPs and 65 FWs. The test for the difference in the slope of the regression line was applied to the relationship between the thermal environment and physiological and psychological responses. If the slopes were parallel, a test for the equality of intercepts was performed. The p-value represents the significant difference in the intercept.

In addition, since the occupations that were measured at the CS (FWs and RPs) were the same as the occupations in AC experiments, the relationship between the ER and rate of naked BWL of CWs wearing/not wearing VWW was determined based on the results of the AC experiment.[7] The rate of naked BWL (sweat rate + insensible perspiration), which is difficult to measure at the CS, was estimated from the regression formula and the effects of wearing/not wearing VWW and WS on the rate of naked BWL were evaluated.

3. Results

3.1 Thermal environment

Figure 3 shows the measurement results of the thermal environment on the ground. Figure 3A displays the change in air temperature for 5 days. The air temperature was less than 30°C on August 3 and 4, but it exceeded 30°C after August 5. Figure 3B illustrates the change in EGT. Although there was almost no difference between the air temperature and EGT, the air temperature was higher than the EGT during PM2 owing to the location of the globe thermometer. Only on August 8 the EGT was higher than the air temperature, as it was 1.5-2.7°C higher from AM2 to PM2. The higher EGT on August 8 appeared to be caused by the ground surface temperature increase due to the large solar radiation on that day (Figure 3C). The incident solar radiation was the highest in AM2. Figure 3D and E depict the changes in air velocity and absolute humidity, respectively. The air velocity tended to reduce in the afternoon, whereas the absolute humidity increased in the afternoon on August 3 and 4 and showed a relatively constant value from August 5 to 8.

3.2 Local and MST

Figure 4A indicates the relationship between air temperature and MST, whereas Figures 4B-E display the relationship between the air temperature and local skin temperatures. The test results showed that the regression lines were parallel and that the MST of CWs not wearing VWW was significantly higher (by 0.57°C) than that of CWs wearing VWW regardless of air temperature ($P < .001$). The chest skin temperature, which is affected by the wind from an electric fan, of CWs not wearing VWW was significantly higher (by 1.61°C) than that of CWs wearing VWW ($P < .001$). Furthermore, the forearm skin temperature of CWs not wearing VWW was also significantly higher (by 0.41°C) than that of CWs wearing VWW ($P = .041$). In the AC experiment,[7] although the chest skin temperature of CWs not wearing VWW was higher than that of CWs wearing VWW, no significant difference was observed in the forearm skin temperature. The difference in the results for the forearm skin temperature may be attributed to solar shading by wearing VWW at the CS. The regression formula did not reveal significant differences in the thigh and lower leg skin temperatures.

3.3 Relationship between MST and psychological responses

Figure 5A presents the relationship between MST and thermal sensation at the end of work. No significant difference was found between wearing and not wearing of VWW. The average activity during work was approximately 2.2 MET (1.77 met) [Note 3], and the MST when people feel thermal neutrality, which was calculated using Fanger's formula, was estimated to be 32.8°C. The MST when people feel thermal neutrality was estimated to be 31.8°C using the regression line of Figure 5A. Thus, the MST when people feel thermal neutrality obtained in the experiment was approximately 1°C lower than that estimated from Fanger's formula. The participants were also expected to select "very hot" when the MST was approximately 35.4°C.

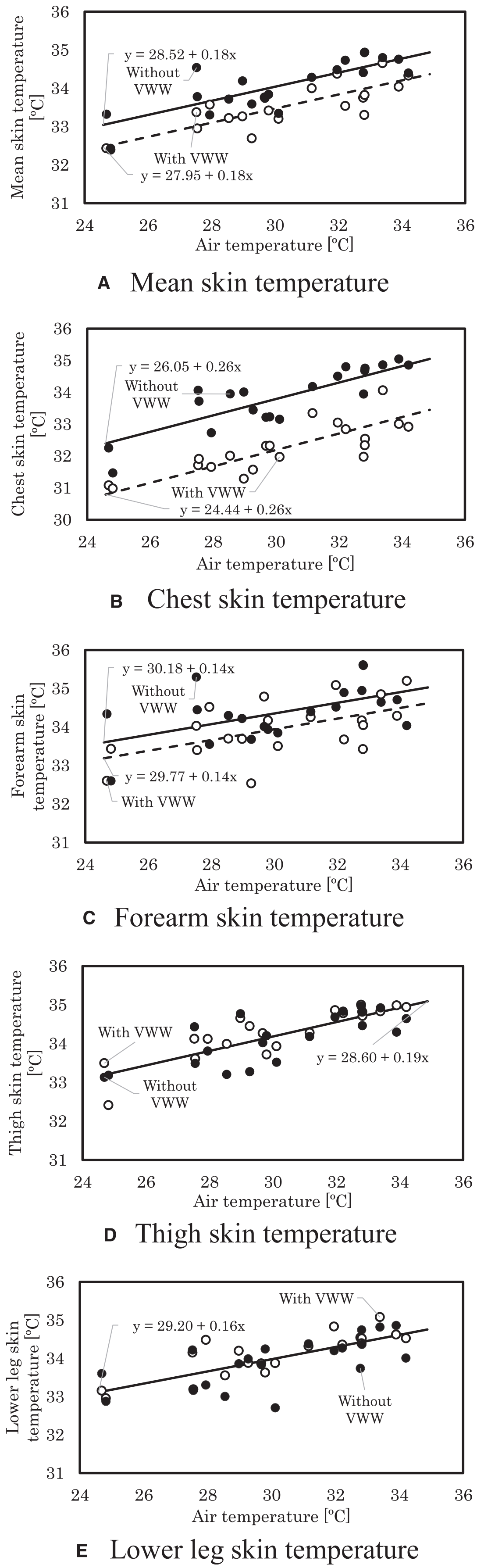
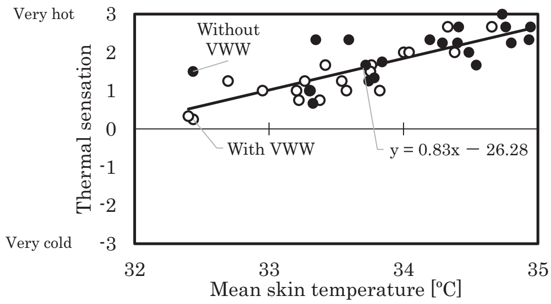
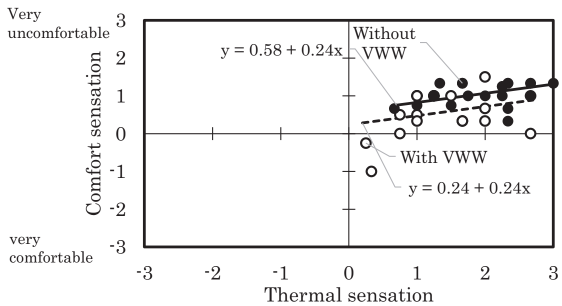


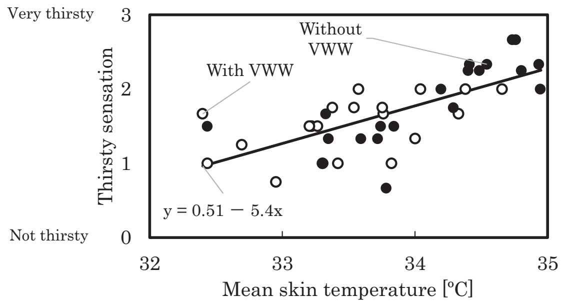
Figure 4. Mean and local skin temperatures. (A) Mean skin temperature. (B) Chest skin temperature. (C) Forearm skin temperature. (D) Thigh skin temperature. (E) Lower leg skin temperature



A Mean skin temperature vs. thermal sensation



B Thermal sensation vs. comfort sensation

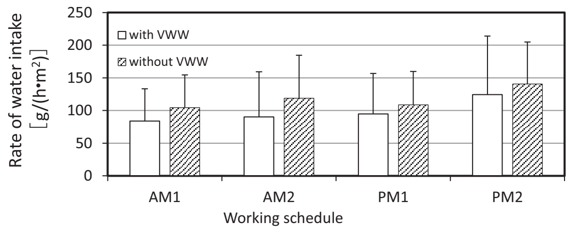


C Mean skin temperature vs. thirsty sensation

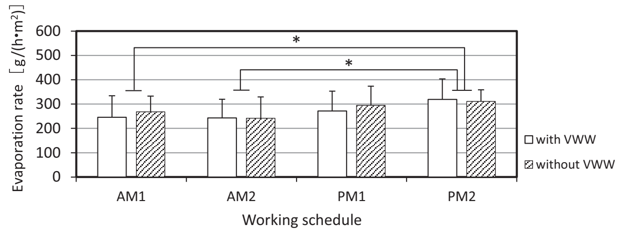
Figure 5. Relationship between physiological and psychological responses. (A) Mean skin temperature vs. thermal sensation. (B) Thermal sensation vs. comfort sensation. (C) Mean skin temperature vs. thirsty sensation

Figure 5B shows the relationship between the thermal and comfort sensations. The CWs indicated that they became “uncomfortable” to “slightly uncomfortable” even though they indicated that they felt “very hot.” The test showed that the two regression lines were parallel, and the comfort sensation of CWs not wearing VWW was significantly higher (by 0.35) than that of CWs wearing VWW ($P < .05$). The discomfort sensation was slightly reduced by wearing VWW even with the same thermal sensation.

Figure 5C depicts the relationship between the MST and thirsty sensation at the end of work. The CWs appeared to be thirsty when the MST increased. No significant difference between wearing and not wearing of VWW was observed.



A Mean rate of water intake at each working schedule



B Mean evaporation rate at each working schedule

Figure 6. Comparisons of mean rate of water intake and evaporation rate with and without VWW at each working schedule. (A) Mean rate of water intake at each working schedule. (B) Mean evaporation rate at each working schedule

3.4 Effects of wearing/not wearing VWW and WS on physiological reactions

Figure 6 shows the comparison of the mean RWI and ER with and without VWW at each WS.

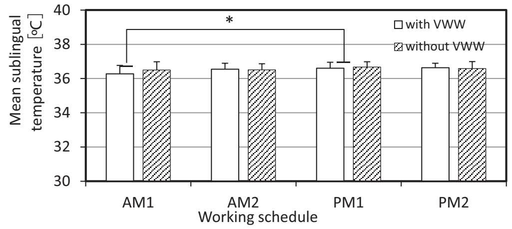
As displayed in Figure 6A, there was no significant difference in RWI. However, the RWI of CWs wearing VWW was slightly lower than that of CWs not wearing VWW at all WSs. Moreover the RWI of 132 g/(h·m^2) in PM2 tended to be larger than that of other WSs, which was approximately 100 g/(h·m^2). The average amount of water consumed during work excluding breaks was approximately 1300 g/day/person.

There was no interaction in the ER between WS and VWW (see Figure 6B), and the effect of WS alone was significant (F (1, 3) = 5.910, $P < .01$). A multiple test for work time using Tukey’s HSD (5% level) revealed the following significant differences: AM1 (256.8 g/(h•m^2)) < PM2 (315.2 g/(h•m^2)), and AM2 (242.5 g/(h•m^2)) < PM2.

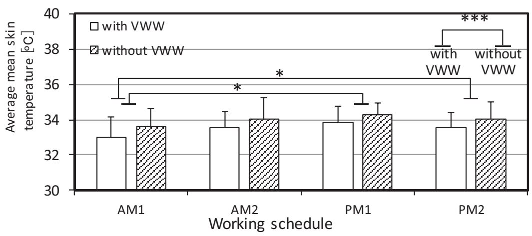
Figure 7 illustrates the results of a two-way ANOVA using VWW and WS as independent variables and sublingual temperature, MST, HR, and activity as dependent variables.

As shown in Figure 7A, there was no interaction in sublingual temperature between WS and wearing/not wearing VWW, and only the effect of WS was significant ($F(1, 3) = 2.837$, $P < .05$). Multiple comparisons based on Tukey’s HSD method (5% level) for WS revealed a significant difference between AM1 and PM1. The sublingual temperature of PM1 (36.64°C) was significantly higher than that of AM1 (36.38°C). Although there was no significant difference, the sublingual temperature of PM2 (36.61°C) was high and almost the same as that of PM1.

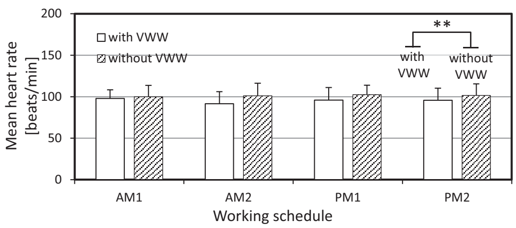
There was no interaction in MST between WS and wearing/not wearing VWW (see Figure 7B), and the effects of WS (F (1, 3) = 3.899, $P < .05$) and VWW (F (1, 1) = 11.977, $P < .001$) were significant. Multiple comparisons using Tukey’s HSD method (5% level) demonstrated that the MST



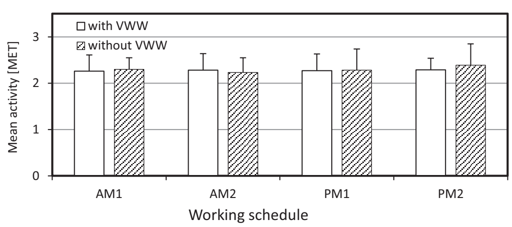
A Mean sublingual temperature at each working schedule



B Average mean skin temperature at each working schedule



C Mean heart rate at each working schedule



D Mean activity at each working schedule

Figure 7. Comparisons of mean sublingual temperature, skin temperature, heart rate measured at chest, and mean activity with and without VWW across working schedules. (A) Mean sublingual temperature at each working schedule. (B) Average mean skin temperature at each working schedule. (C) Mean heart rate at each working schedule. (D) Mean activity at each working schedule

of AM1 (33.30°C) was significantly lower than those of PM1 (34.05°C) and PM2 (33.91°C). In addition, the MST for those wearing VWW (33.47°C) showed a significantly lower value than for those not wearing VWW (34.05°C).

As indicated in Figure 7C, although there was no interaction in the HR between WS and wearing/not wearing VWW, a significant effect due to VWW ($F(1, 1) = 10.135$, $P < .01$) was observed. The HR of CWs wearing VWW (92.8 bpm) was significantly lower than that of CWs not wearing VWW (101.6 bpm). Although no significant difference was observed, the HR of PM1 (99.9 bpm) and PM2 (99.7 bpm) tended to be higher than those of AM1 (93.5 bpm) and AM2 (96.4 bpm).

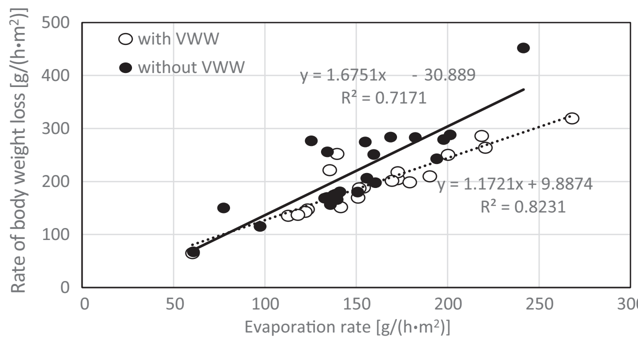


Figure 8. Relation between evaporation rate and rate of body weight loss with and without VWW measured in the artificial climate chamber at two fixed temperatures (29°C, and 34°C)

Although there was no significant difference, the average 2.34 MET of PM2 was approximately 5% higher than those of the other periods (Figure 7D). The reason for the activity increase in PM2 was presumed to be the need to complete the target work for the day. The average activities during the WS for the RPs and FWs were 2.19 and 2.36 MET, respectively, which were higher than the 2.08 and 2.00 MET, respectively, of the simulated work in the AC experiment. The FWs had more activity than the RPs because the FWs had more work on the sixth floor and walked more compared to the RPs, who mainly worked on the ground.

4. Discussion

4.1 Regression formula between ER and rate of naked BWL

To estimate the rate of naked BWL from the ER at the CS, a linear approximation between the rate of naked BWL and ER with and without VWW in the AC was obtained (Figure 8). The rate of naked BWL of CWs wearing VWW had less variation than that of CWs not wearing VWW and the slope of the approximate line was smaller. The ER of CWs wearing VWW was larger than that of CWs not wearing VWW even though the rate of naked BWL for CWs wearing VWW was the same as for those not wearing VWW.

4.2 Effects of VWW and WS on the rate of naked BWL

The rate of naked BWL at the CS was calculated from the ER at the CS based on the regression formula presented in section 4.1.

Figure 9 shows the results of a two-way ANOVA. Although there was no interaction between the WS and VWW, the effect of WS was significant (F (1, 3) = 5.977, $P < .001$); moreover a significant effect was also observed for VWW (F (1, 1) = 35.852, $P < .001$). Multiple comparisons by Tukey's HSD method (5% level) revealed significant differences between AM1 and PM2 and between AM2 and PM2. The rate of naked BWL of PM2 (435.0 g/(h·m^2)) was significantly higher than those of AM1 (355.5 g/(h·m^2)) and AM2 (347.6 g/(h·m^2)). The rate of naked BWL of CWs wearing VWW (332.0 g/(h·m^2)) was significantly lower than that of CWs not wearing VWW (445.6 g/(h·m^2)).

4.3 Effect of VWW on the relationships between air temperature and ER and rate of naked BWL

Figures 10A-C display the relationships between air temperature and rate of naked BWL, air temperature and ER, and rate of naked BWL and RWI, respectively.

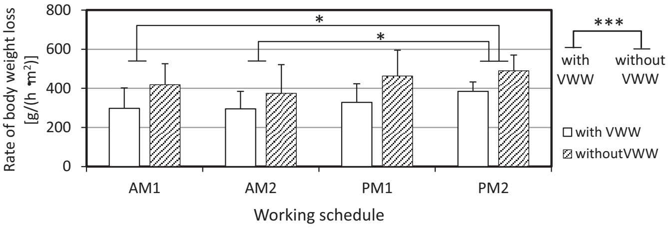


Figure 9. Comparison of mean rate of body weight loss with and without VWW across schedules

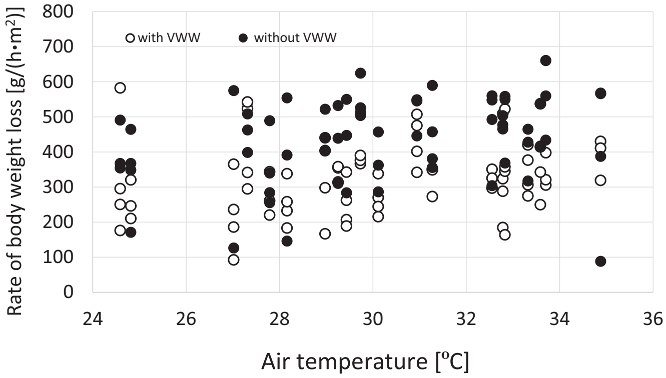
With regard to the relationship between air temperature and rate of naked BWL (Figure 10A), the rates of naked BWL of CWs wearing VWW were distributed in a range with a lower value than that of CWs not wearing VWW, and the effect of VWW was confirmed. Such lower rate of naked BWL can be caused by the lower MST as the sweat rate is determined by the effects of skin temperature and core body temperature.[10]

As illustrated in Figure 10B, the ERs at the same temperature with and without VWW were mixed. Thus, an effect of VWW on the ER was not observed, similar to the results of the AC experiment.[7]

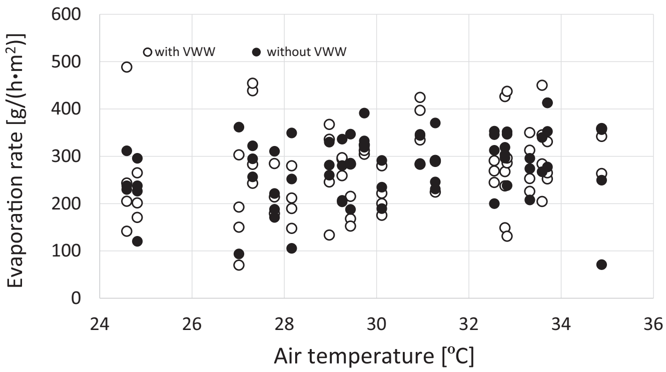
The ratio of RWI to rate of naked BWL of CWs not wearing VWW was 1/2 to 1/3 smaller than that of CWs wearing VWW (Figure 10C). Therefore, CWs not wearing VWW are more likely to develop dehydration than those wearing VWW. In addition, the average RWI during a WS was approximately 110 $g/(h{\cdot}m^2)$. Assuming an average body surface area of 1.8 m^2, the CWs consume approximately 200 g/h of water, and the average rate of naked BWL of CWs not wearing VWW was 445.6 $g/(h{\cdot}m^2)$. Therefore, the CWs lost approximately 800 g/h of water, which is four times the water intake value. It is thus important to rehydrate during breaks.

Those wearing VWW showed significantly lower SCCs and HRs in the AC experiment at 34°C. No significant difference was observed between the rate of naked BWL and ER with and without VWW. However, those wearing VWW showed significantly lower rates of naked BWL (Figure 9) and HRs (Figure 7C) in the air temperature range of 24–35°C at this CS measurement. However, the VWW (Figure 6B) showed no significant effect on the ER as in the AC experiment.

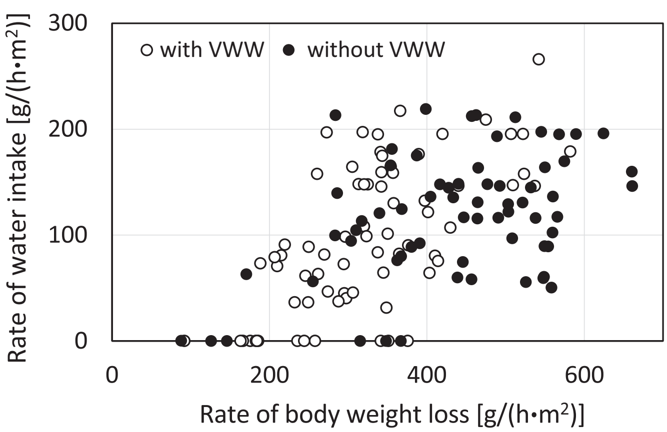
These results suggest that wearing VWW can reduce sweating and prevent dehydration. However, the rate of naked BWL during PM2 near the evening (Figure 9) was significantly higher than those in the morning periods, that is, AM1 and AM2. Therefore, CWs working late in the afternoon are particularly prone to dehydration. The results estimated from the path model of Yamazaki et al[7] revealed that the HR during PM2 was approximately 6 bpm higher than that during AM1. The higher HR during PM2 caused the MST to be 0.7°C higher in PM1 and 0.6°C higher in PM2 compared to that in AM1 ($F(1, 3) = 3.899$, $P < .05$) and the sublingual temperature to be 0.3°C higher in PM1 and PM2 than in AM1 ($F(1, 3) = 2.837$, $P < .05$) as indicated in Figure 7. This was presumed to be because the air temperature was high in the afternoon and the air velocity tended to decrease (Figure 1); moreover the activity during PM2 was slightly higher than that in the AM periods (Figure 3D). It is necessary to take measures such as reducing the spike in activity, which is otherwise almost constant throughout the day, at PM2.



A Relation between air temperature and rate of body weight loss



B Relation between air temperature and evaporation rate



C Relation between body weight loss and rate of water intake

Figure 10. Verification of the effect of VWW on rate of body weight loss, evaporation rate, and rate of water intake. (A) Relation between air temperature and rate of body weight loss. (B) Relation between air temperature and evaporation rate. (C) Relation between body weight loss and rate of water intake

5. Conclusion

In this study, measurements were carried out at an actual CS to verify the effects of VWW and WS on skin temperature, BWL, and so on. The air temperature was below 30°C on August 3 and 4, and it exceeded 30°C after August 5.

A test for the difference in regression line was applied to the relationship between air temperature and skin temperature. The MST and chest and forearm skin temperatures of CWs not wearing VWW were significantly higher than those of CWs wearing VWW. In the AC experiment, although the chest skin temperature of CWs not wearing VWW was higher than that of CWs wearing VWW, no significant difference was observed in the forearm skin temperature. This difference in the results of the forearm skin temperature may be because of solar shading when wearing VWW at the CS.

No significant difference was observed between the MST and thermal sensation with and without VWW. The comfort sensation of CWs not wearing VWW was significantly higher than that of CWs wearing VWW. The discomfort sensation was slightly reduced by wearing VWW even with the same thermal sensation.

Regarding the relationship between air temperature and ER, the effect of VWW on the ER was not established. Concerning the relationship between the air temperature and rate of naked BWL, the rate of naked BWL of CWs wearing VWW was distributed in a range of a lower value than that of CWs not wearing VWW. The effects of VWW obtained in the AC experiment were also observed in the CS measurement. However, the effects of VWW on skin temperature and BWL were observed in the CS at an air temperature range of 24–35°C, whereas those in the AC experiments were observed only at 34°C. This was because the activity of CWs at the CS was higher than that in the AC experiment for simulated work; moreover unlike in the AC experiment, the CWs were exposed to thermal solar radiation.

Since the rate of naked BWL during PM2 near the evening (Figure 9) was significantly higher than those during AM1 and AM2, CWs in late work hours in the afternoon were prone to dehydration. As a result, the HR and MST of the PM periods were higher than those of the AM periods. This was presumed to be because the thermal environment deteriorated in the afternoon and the activity during PM2 was slightly higher than those during the morning periods. It is necessary to take measures such as reducing the spike in activity, which is otherwise almost constant throughout the day, at PM2 in the afternoon. Managers at CSs need to inform CWs that more water intake is necessary to prevent dehydration during the late afternoon shifts.

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Disclosure

The authors have no conflict of interest.

Notes

Note 1) Toilet use during work was recorded, but urine volume was not measured. The use of towels during work was allowed. However, sweat contained in the towels was not measured. There were no restrictions on drinking water or eating during breaks. The CWs had breaks and lunches mainly in an air-conditioned room at 30°C or lower, with some resting outdoors.

Note 2) During the experiment, 1 was "very hot" and 7 was "very cold." However, in this paper, the values were replaced with −3 to +3 as shown in Table 4.

Note 3) The unit of MET represents the ratio of the rate of energy spent during working to that when resting, where the oxygen intake at rest, that is, $VO_2 = 3.5$ [mL/(kg·min)], is 1 MET. The unit "met" expresses how many times the current work is equivalent to the metabolic rate at rest when sitting on a chair; 1 met = 58.15 W/m^2 is used in the thermal equilibrium between the human body and the environment. Since calculating MET requires VO_2, respiratory quotient R, and body surface area A_{Du}, this study assumes that $A_{Du} = 1.8$ m^2 (height of 1.7 m and weight of 70 kg) and R = 0.92.

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