Asia-Pacific Journal of Atmospheric Sciences (2023) 59:447–458
https://doi.org/10.1007/s13143-023-00326-4

Online ISSN 1976-7951
Print ISSN 1976-7633

ORIGINAL ARTICLE

Field-based Heatwave Risk Assessment of Outdoor Workers Measured by Wearable Sensors

Ara Kim[1] · Gayoung Yoo[2]

Received: 22 March 2023 / Revised: 3 April 2023 / Accepted: 11 April 2023 / Published online: 24 April 2023

Abstract

Increasing heatwave frequency due to climate change threatens outdoor workers' health. We aimed to assess the on-site heat strain level of outdoor workers using wearable sensors and identify the factors for consideration in developing individual-based heat adaptation strategies. Seven road construction workers were recruited and asked to wear necklace-form temperature loggers and smartwatches monitoring heart rate (HR). The questionnaire was delivered daily to ask about their psychological comfort level during work. Workers were exposed to up to 5.4 °C higher temperature than the official air temperature, indicating that the national heatwave alarm does not reflect on-site heat conditions. Based on the measured HR data, heat strain levels were defined. When HR exceeded the level of "180-age," we assumed extreme heat strain occurred, which requires immediate cessation of work. When HR exceeded 40% of the individual heart rate reserve (the difference between the maximum and resting HR), we assumed high heat strain occurred, indicating a stressed condition. High heat strain occurred in all workers on 9 of the 13 monitored days, whereas the official heatwave alarms were issued only on four dates. Additionally, three workers experienced extreme heat strain on two dates. The main factor for workers experiencing extreme heat strain was age. Comparing the heat strain levels from HR with the survey results, we found that the older workers considered their condition comfortable even under extreme and high heat strain. Thus, an individual sensor-based early-warning system is needed to prevent heat strain not perceived by outdoor workers. The findings emphasize the need for a personalized adaptation strategy for heatwaves and will be a baseline for developing a new work manual that mainstreams climate change impacts.

Keywords Climate change · Adaptation · Outdoor workers · Wearable sensor · Heatwave · Heat strain

1 Introduction

Outdoor workers are at a high risk of heat stress due to the increasing frequency and intensity of heatwaves caused by climate change. In the last 20 years, the productivity of outdoor workers was reported to have decreased by 5.3% on average worldwide (Watts et al. 2018). The decrease in productivity is closely related to the reduction in labor hours. The International Labor Organization (2019) predicts that the total number of labor hours will reduce by 2030 due to high ambient temperature, and it would correspond to a loss of 2.4 trillion USD. The World Health Organization (1948) declared that "any decline in a worker's performance of daily activities due to heat or extreme weather should be considered a 'health effect' of climate conditions." Temperature rise also increases the likelihood of injury such as falling from heights or mishandling dangerous machinery during outdoor work. It was reported that the risk of injury would increase by 5–7% when the temperature is between 30 and 32 °C, and 10–15% above 37 °C, relative to 15 °C (Park et al. 2021). Additionally, the morbidity and mortality from heat-related illness (HRI) are expected to increase by an average of 18% and 35%, respectively, per every 1℃ (Faurie et al. 2022).

In Korea, outdoor workers account for 14.1% (about 3.3 million) of the economically active population. The incidence rate of HRI among them is about 8.2 times

Responsible Editor: Woosuk Choi.

Gayoung Yoo
gayoo@khu.ac.kr

[1] Department of Applied Environmental Science, Kyung Hee University, Yongin, Republic of Korea

[2] Department of Environmental Science and Engineering, Kyung Hee University, Yongin, Republic of Korea

higher than that in other occupation groups (KEI 2020). In 2018, heatwaves reduced work efficiency, resulting in an economic loss of approximately 290 million USD (KEI 2020). A heatwave alarm system, which is currently operated by the Korea Meteorological Administration, could mitigate these negative impacts of heatwave on outdoor workers. The system is issued as a heatwave watch or warning when the daily maximum temperature is 33℃ and 35℃ or higher for two consecutive days or more, respectively. When the heatwave alarm is issued, the Ministry of Employment and Labor recommends regular rest periods of 10 min per hour and the adjustment of working hours to minimize the time spent in outdoor work during the sweltering heat. However, the current alarm system standards are based on temperatures beyond which excessive fatalities occur (Park et al. 2008). These standards are too high to reflect the less fatal effects, such as fatigue, dizziness, and heat stroke, that influence performance and health during heat-exposed work. Additionally, since the air temperature data used to issue an alarm is an average value of official data points from automatic weather stations (AWS), it would be considerably different from the temperature that outdoor workers are exposed to in the field. The directly exposed temperature (DET) of outdoor workers is generally reported to be higher than the official air temperature by AWS, and the difference between the two reached up to 10℃ (Bernhard et al. 2015; Uejio et al. 2018).

When there is a heatwave, human bodies physiologically respond in a way that transfers the heat load back into the environment (ACGIH 2007; NIOSH 2016), which is defined as heat strain. Hence, heat strain could be a very useful indicator of health risk caused by heatwave. Human heat strain can generally be measured using core body temperature or heart rate (HR), and they have been usually monitored under a controlled environment because their monitoring required special sensors usually connected with wires (Logan and Bernard 1999; Notley et al. 2018; Parsons 2013).

The emergence of wearable sensors dramatically overcame the two limitations mentioned above. Portable and attachable temperature sensors can measure the outdoor workers' DET. Furthermore, smartwatches have enabled us to continuously monitor individual HR on-site, which is used to quantify workers' heat strain levels in real-time (NIOSH 2016).

The thermal comfort level, which is commonly measured by a survey asking how the outdoor workers actually "feel" during their work, can be an important proxy to measure the perceived degree of heat stress (Notley et al. 2018). However, as the survey questionnaire is generally answered once a day after work, the answers cannot reflect the real-time comfort level, and their perceived heat stress would be averaged throughout the day. By comparing the survey results with real-time continuous HR monitoring results, we would like to find the blind spot in developing individual heat adaptation strategies.

The objectives of this study were (1) to develop a method to assess the outdoor workers' heat strain using continuous HR data monitored by wearable sensors, and (2) to identify the factors to be considered in developing individual-based heat adaptation strategies. Comparison between the levels of heat strain and perceived thermal comfort level from a questionnaire survey will provide a basis for developing individual-based adaptation strategies.

2 Method

2.1 Study Participants and Workplaces

Participants of this study were seven workers at road construction sites in Dongjak-gu, Seoul, Korea. Construction workers are one of the most vulnerable outdoor workers performing strenuous physical work during heatwaves (Acharya et al. 2018). Of all the reported HRIs in South Korea, 47.9% were related to construction workers, and their accident rate over the past 10 years was the highest among outdoor workers (KOSHA 2018).

On the first day of the experiment, we collected data on participants' age, sex, and work years, and measured personal physical attributes, including height, weight, body mass index (BMI), body fat, muscle mass, and body water, using the body composition scale (Xiaomi Mi Body Composition Scale 2, Xiaomi Corp., China). All participants agreed to wear the proposed personal monitoring devices for DET and HR measurement and to record daily logs of details such as working clothes and time and the number of breaks. They had lunch between 12:00 p.m. and 1:00 p.m. and rested at least twice a day for 10–15 min each, although their break times varied by individual.

The workplaces were on four roads located in (a) Noryangjin, (b) Bon, (c) Heukseok, and (d) Sadang in Dongjak-gu, Seoul, Korea (Fig. 1). On average, the roads were 10.3 m in width and 131 m in length (Table 1). All participants worked at the same site from July 25 to August 31, 2022, for four days in each workplace. However, because each worker had days off on different dates, the total days of work for each worker were not identical (A: 12, B: 11, C: 14, D: 16, E: 10, F: 13, G: 12). The experiment procedure was approved by the Institutional Review Board of Kyung Hee University (approval number: KHGIRB-22-315) (Fig. 2).

2.2 Collecting Official Air Temperature and Directly Exposed Temperature Data On-Site

To compare the official air temperature and outdoor workers' DET, we collected official air temperature data from all

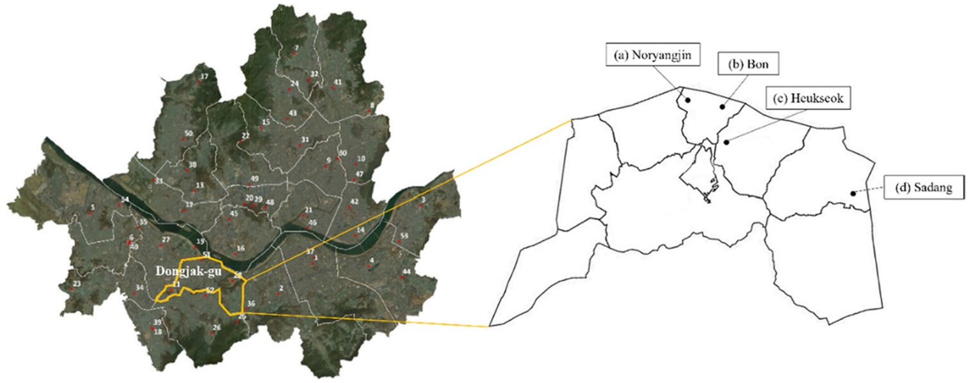

Fig. 1 Locations of the 54 automatic weather stations (red dots) and the workplaces (yellow line) in Seoul as a municipal scale issuing heatwave alarm

Table 1 The characteristics of the workplaces

Item	Road (a) Noryangjin	Road (b) Bon	Road (c) Heukseok	Road (d) Sadang	Mean
No. of lanes	3	3	3	4	3.3
Road length (m)	110	125	152	137	131
Road width (m)	10.1	9.8	10.1	11.2	10.3

of the 54 AWS in Seoul, which were recorded at a 2-minute interval from 8:00 a.m. to 5:00 p.m. from July 25 to August 31, 2022 (Table 2). The average value of the collected air temperatures was calculated, which is the standard for issuing a heatwave alarm on a municipal scale (Unit: Si) (Fig. 1). During the same period of collecting the official air temperature, the DET data were measured using the RC-5 Temperature Data logger (Elitech Ltd., United Kingdom) (80 (L) × 25 (W) × 12 (H) mm, 35 g) (Table 2; Fig. 3a).

Fig. 2 Experiment procedure

Table 2 Air temperature and directly exposed temperature on each working day

Working day	Air temperature (℃)				Directly exposed temperature (℃)			
	Mean	SD	Min	Max	Mean	SD	Min	Max
1	30.4	2.9	25.8	35.0	32.7	2.8	28.1	38.0
2	31.5	2.2	27.9	35.7	34.7	2.2	30.4	39.5
3	27.5	1.8	23.5	28.8	31.2	2.1	26.4	36.1
4	26.7	1.1	24.8	28.4	29.9	1.1	27.6	32.9
5	27.6	2.1	23.5	30.7	30.6	1.5	27.4	34.1
6	28.3	2.4	23.1	33.1	32.8	1.7	28.5	35.0
7	29.8	2.4	24.8	33.0	33.0	2.0	29.7	38.6
8	27.3	1.4	25.5	30.4	31.8	1.2	29.1	35.0
9	27.1	1.4	25.5	29.8	31.9	2.0	27.6	32.4
10	28.2	1.9	23.9	30.5	29.9	1.1	27.7	32.4
11	24.9	1.7	21.9	27.3	28.3	1.5	25.9	31.2
12	27.7	2.7	23.1	33.0	30.5	2.0	27.1	34.2
13	28.3	1.9	22.6	33.2	28.6	1.0	26.5	34.3
14	29.1	1.6	24.2	33.9	30.2	1.7	27.0	35.5
15	28.0	2.1	20.1	31.2	26.8	0.6	25.5	36.7
16	24.6	1.6	21.1	27.0	27.9	2.1	24.5	32.4
Total mean	27.9				30.7			

The RC-5 measures a temperature range of -30℃ to 70℃ with a resolution of 0.1℃ and an accuracy of ± 0.5 (Elitech 2023). The RC-5 temperature sensor was validated with TESTO 480 (Testo Ltd., Germany), which is widely used for measuring air temperature in the field study due to high reliability (Deevi and Chundeli 2020). All the participants were asked to wear the RC-5 in a necklace form (Fig. 3c). We also checked the dates on which the Korea Meteorological Administration issued heatwave alarms during the experiment period and compared data to the dates when the heatwave alarm should have been issued if using the average official air temperature closest to the workplace as a smaller municipal scale and DET data.

2.3 Measuring Heart Rate and Thermal Comfort Level

HR was measured using a smartwatch (Mi-band 3, Xiaomi Corp., China) equipped with a photoplethysmography-based sensor to detect blood volume changes in the microvascular bed of tissue via reflection from or transmission through the tissue (Duck 2013) (Fig. 3b). Each worker wore the smartwatch, which monitored their HR at 2-minute intervals, on their left wrist (Fig. 3c). The HR data during the working hours (8:00 a.m. to 5:00 p.m.) was divided into HR at work (HR_{work}) and HR at rest (HR_{rest}) based on the records of lunch and break times.

After each day's work, we surveyed psychological comfort levels for how outdoor workers felt thermally during the work (Fig. 4). All the workers were required to complete a survey via the voting system of a messenger application, "Kakao Talk," on every working day. Since the survey was conducted in a one-on-one chat room to avoid answer bias in the results, participants were blinded to others' answers. The query was adopted from the studies by Huang et al. (2017) and Spagnolo and De Dear (2003). The survey comprised two questions—one related to the clothes and equipment, and the other related to their comfort levels during work. Regarding comfort level, the workers were asked to rate thermal comfort on a 7-point scale ranging from very discomfortable to very comfortable (-3: very discomfortable, -2: discomfortable, -1: slightly discomfortable, 0: neutral, 1: slightly comfortable, 2: comfortable, 3: very comfortable).

2.4 Calculation of Heat Strain

Heat strain was quantified using the monitored HRs. To protect the health of workers, the American Conference of Governmental Industrial Hygienists (ACGIH 2007) set the threshold limit value for heat strain as "sustained (at least three minutes) HR in excess of 180 beats per minute (bpm) minus the individual's age." This has been globally used as an occupational exposure limit requiring immediate cessation of work. Therefore, we defined "extreme heat strain" (EHS) as HR exceeding "180-age" (bpm) observed more than twice in a row for at least four sustained minutes during work.

Even though the HR does not increase as high as the EHS level, the sub-level of EHS could still cause heat stress conditions (Bernard and Kenney 1994; Matsuura et al. 2019). We defined this level as "high heat strain" (HHS) because it would also cause health problems for workers (von Scheidt et al. 2019; Schlagbauer and Heck 1948). To define HHS, we used the concept of the heart rate reserve (HRR), which is widely used as a reliable measure of cardiovascular strain (Borresen and Lambert 2009). Using the maximum HR and the HR at rest, HRR was calculated based on the following equation:

$$HRR(\%) = \frac{HR_{work} - HR_{rest}}{HR_{max} - HR_{rest}} \times 100 \quad (1)$$

where HR_{work} is the measured average HR during the working hour, HR_{rest} is the measured average HR during the break and lunchtime, and HR_{max} is the individual's maximum HR

(a) The RC-5 temperature logger (b) Smartwatch (Mi-band 3) (c) The appearance wearing the necklace-form RC-5 temperature logger and smartwatch

Fig. 3 Wearable sensors monitoring outdoor workers' directly exposed temperature and heart rate. **a** The RC-5 temperature logger. **b** Smartwatch (Mi-band 3). **c** The appearance wearing the necklace-form RC-5 temperature logger and smartwatch

Fig. 4 The questionnaire of the thermal comfort survey

Thermal Comfort Survey

NOTE: This survey is entirely voluntary.
If you do not wish to complete it, or any part of it, you are under no obligation to do so.

Question 1: CLOTHES & EQUIPMENT

Please tick all the items closest to what you were wearing during the work.

Shorts	Long pants
Short sleeved shirt	Long sleeved shirt
Shoes AND/OR socks	Sandals OR slipper
Cap	Cool wristlets
Portable fan	Parasol

Question 2: THERMAL COMFORT LEVEL

Please tick the comfort level for how you thermally felt during the work.

Very Discomfortable	Discomfortable	Slightly Discomfortable	Neutral	Slightly Comfortable	Comfortable	Very Comfortable

estimated as a function of age using the following equation (Tanaka et al. 2001):

$$HR_{max} = 208 - (0.7 \times age) \quad (2)$$

We defined HHS as the HR corresponding to the level of 40% HRR. The reason for choosing the level of 40% HRR was based on the results of Hashiguchi et al. (2020) and Chan and Yang (2016), which reported that the physiological strains for outdoor workers occurred at this level in Japan and Hong Kong, respectively. Although the Korean climate zone is not the same as in these countries, the recent summer temperature records suggest that the metropolitan areas of Korea have experienced a subtropical climate due to the urban heat island effect caused by climate change (Park et al. 2013; Yun et al. 2012). When we compared the mean maximum air temperature of August 2019 in Korea with those of Japan and Hong Kong, they were almost identical (35.5℃ in Japan, 35.6℃ in Hong Kong, and 35.7℃ in Korea) (WorldData.info 2023). Additionally, the mean relative humidity and wind velocity among the three countries were also quite similar (79% and 5.1 m/s in Japan, 81% and 4.9 m/s in Hong Kong, and 78% and 4.8 m/s in Korea) (WorldData.info 2023). Hence, we adopted the same HRR standard for HHS as Japan and Hong Kong, and the HR corresponding to 40% HRR was calculated using the following equation derived by the Eq. 1:

$$Heart\ Rate\ of\ 40\%\ HRR(bpm) = 0.4 \times \left(HR_{max} - HR_{rest}\right) + HR_{rest} \quad (3)$$

2.5 Statistical Analyses

Descriptive statistical analysis was performed on the workers' age, work years, height, weight, BMI, body fat, muscle mass, and body water. Demographic characteristics were identified using the mean and standard deviation of the results of descriptive statistics. Based on the analysis of variance (ANOVA), the difference between official air temperature from AWS and DET was tested.

A stepwise regression analysis was conducted to extract the critical factor that contributed the most to the number of days in which heat strain (HHS and EHS) occurred. It is a method of multiple linear regression through which all independent variables are compared in terms of their contribution to the dependent variable (Zeng et al. 2022). The variables applied to the stepwise regression analysis were age, work years, BMI, body fat, muscle mass, and body water. All statistical analyses were performed using SAS software, Version 9.4.

3 Results and Discussions

3.1 Participant Characteristics

Seven test participants were six male and one female (Table 3). They had three different tasks. Workers A, D, E, F, and G were asphalt-paving workers who used a pickax and shovel to remove old asphalt and pave the roads with fresh asphalt. Worker B was an asphalt-paving operator who sprayed and flattened the asphalt on the surface. Worker C was a signalman who sent signals with flags and words to ensure workers' safety.

The test participants' average age was 40.6 years and the average working year was 2.5 years. While Workers A and C had the longest work experience (five years), Worker F had the shortest (four months). The workers' mean height and weight were 1.7 m and 68.8 kg, respectively. Their mean BMI was 23.3 kg/m^2, which is within the healthy range according to the WHO BMI classification (WHO 2010). On average, the body fat, muscle mass, and body water were 22.1%, 29.4 kg, and 38.9 L, respectively.

3.2 Comparison Between Official Air Temperature and Directly Exposed Temperature On-Site

As a result of ANOVA among outdoor workers' DETs, each outdoor worker's DET was not statistically different. Therefore, we set the average values of all workers' DETs as the representative DET. During the experimental period, the average DETs (30.7℃) were significantly higher than the average air temperature (27.9℃) measured at all of the 54 AWS in Seoul (p-value $<$ 0.01) (Table 2; Fig. 5). The result was consistent with our expectation because the road construction area would be exposed to more direct sunlight, with the asphalt absorbing most of the heat (Pomerantz et al. 2003; Synnefa et al. 2011). The largest difference between DET and the average air temperature (a red star in Fig. 5) was 5.4℃ on the day when the workers worked on Road (c), which is the only road with no median vegetation strip. Vegetation strips have been reported to reduce the temperature of urban roads by up to 3.6℃ (Cha and Lim 2011; Lee et al. 2013). Hence, the DETs of outdoor workers working on Road (c) would have been higher than that on other roads with median vegetation strips. Moreover, the traffic volume on the road on this day was 2707.5 cars/h, the highest during the experiment period (TOPIS 2022). As vehicles generate artificial waste heat and frictional heat between the tires and asphalt, the traffic volume is associated with ambient temperature rise (Son et al. 2015; Lee et al. 2013). Therefore, the amount of artificial waste heat from cars would have contributed to workers' DET increase.

Regarding the current heatwave alarm system which is based on the average of daily maximum temperatures from 54 AWS, the heatwave alarms were issued on four dates during the experimental period (Fig. 6). In contrast, if we choose data from the three AWS closest to the workplace (the Hyun Chung Won station, the Han River station, and the Meteorological Administration station), the heatwave alarms should have been issued on five dates. This indicates that the current heatwave alarm system does not properly reflect the thermal environment of the local workplace. Using data based on the smaller municipal scale could better represent the local thermal environment that people actually experience. The HEAT-SHIELD program operated by the European Union is a good example. It predicts outdoor workers' risk levels based on the air temperature monitored at the AWS located within 5 km of the workplace, and the adoption of this program has improved the heat resilience of workers (Morabito et al. 2019; Morris et al. 2021).

Although the suggested heat alarm system based on the average AWS data close to the workplace can provide better site-specific information, it cannot fully reflect the DET of the workplace itself. Based on the DET data of our experimental site, the heatwave alarms should have been issued on nine dates (two heatwave watches and seven heatwave warnings) (Fig. 6). This discrepancy indicates the need to issue a heatwave warning system based on the workplace. A Hong Kong company, for instance, monitors the workplace's temperature and operates an early-warning system to protect outdoor workers (Yi et al. 2016). This system sends messages to the workers to suggest appropriate intervention strategies to relieve heat stress. Therefore, the early-warning system based on the DET connected to the personal alarm device can help the outdoor workers' heat adaptation by themselves.

Table 3 Individual information of the outdoor workers

Worker	Gender	Age	Work type	Work year	Height (m)	Weight (kg)	BMI	Fat (%)	Muscle (kg)	Body water (L)
A	Male	58	Asphalt paver	5	1.7	66.8	22.8	21.5	27.7	37.9
B	Male	56	Paving operator	3	1.7	64.1	21.7	20.8	34.0	36.9
C	Female	53	Signalman	5	1.6	63.7	25.8	34.4	22.2	30.3
D	Male	46	Asphalt paver	2	1.7	72.3	23.9	21.5	30.1	41.2
E	Male	28	Asphalt paver	1.5	1.8	63.2	20.2	14.3	28.7	39.3
F	Male	23	Asphalt paver	0.3	1.8	69.9	22.6	19.5	29.9	40.8
G	Male	20	Asphalt paver	0.7	1.8	81.4	26	22.8	33.3	45.6
Mean		40.6		2.5	1.7	68.8	23.3	22.1	29.4	38.9
Standard deviation		15.2		1.8	0.1	6.0	2.0	5.6	3.6	4.4

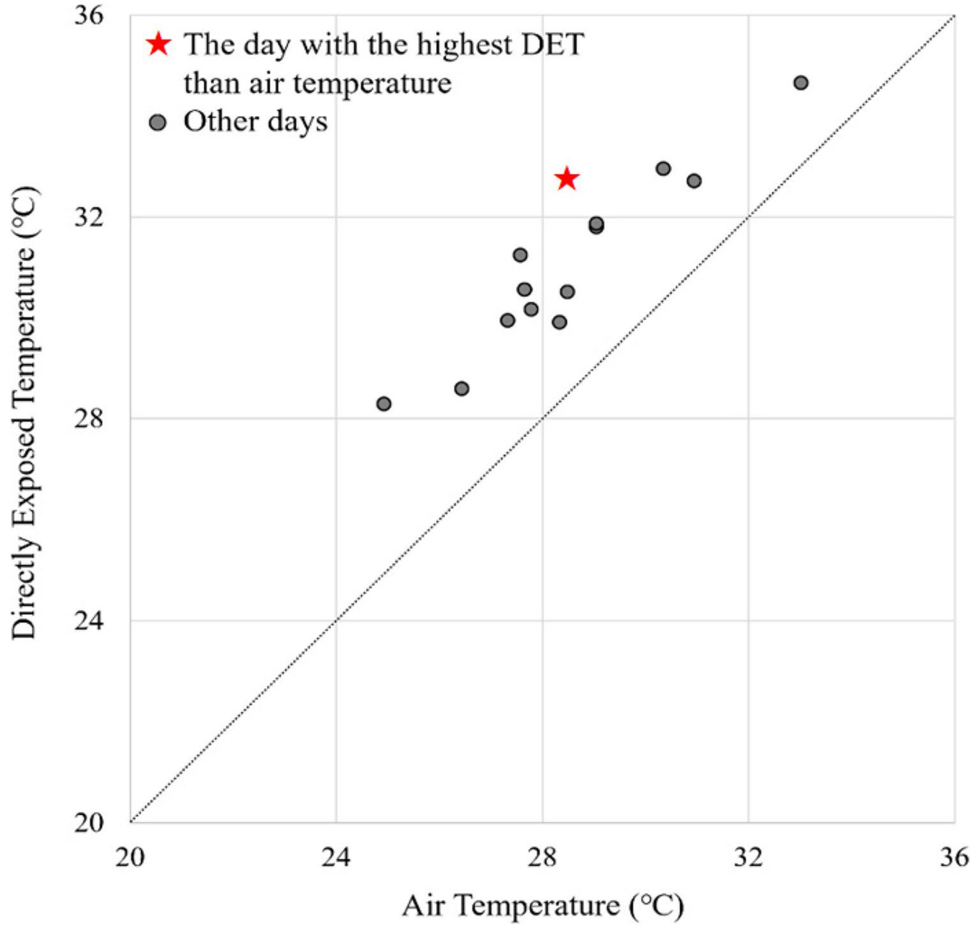

Fig. 5 Relationship between average air temperature and directly exposed temperature (DET)

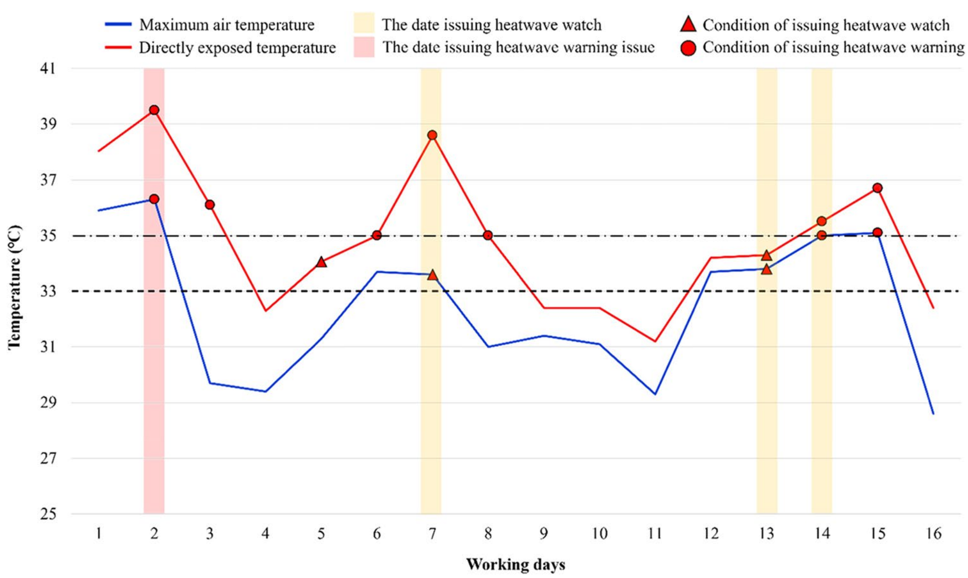

Fig. 6 The daily maximum temperatures and the heatwave alarm issues. Blue line represents the maximum air temperature from the three automatic weather stations closest to the workplace and red line represents the directly exposed temperature to the outdoor workers. Yellow box represents the date of heatwave watch and pink box represents the date of heatwave warning issued by the Korea Meteorological Administration. Red triangle represents the date with the condition of issuing heatwave watch and red circle represents the date with the condition of issuing heatwave warning, considering the maximum air temperature and directly exposed temperature

3.3 Heat Strain and the Key Factor Influencing Heat Strain

The number of days with the HHS occurrences varied with different outdoor workers—A: 12, B: 9, C: 11, D: 14, E: 3, F: 5, and G: 6—for the entire monitoring period (Fig. 7). The percentage of days with HHS, including EHS, was 69.2% in our study, which was much higher than 30.8% reported in a case study conducted in Saudi Arabia by Al-Bouwarthan et al. (2020). The higher occurrence of heat strains in this study despite lower exposure temperatures than those in Saudi Arabia indicates that the Saudi Arabian workers would have better adapted to the heat (Gill and Sleivert 2001; Périard et al. 2016). The workers in the two studies had similar demographic and body characteristics, and the Saudi Arabian workers had longer work experience (5.9 years) than Korean workers (2.5 years).

Meanwhile, EHS occurred in Workers A, B, and C on at least three dates (A: 8, B: 5, C: 3). This indicates that these workers were more vulnerable to heat than others. The result of stepwise regression analysis showed that age was the most common contributing factor for heat strain occurrence (the adjusted R^2 value: 0.747) (Table 4). The average age of Workers A, B, and C was 26.4 years older than the others. Lunde et al. (2016) demonstrated that the cardiovascular load during work increased by up to 29.8% with the age increase of construction workers. Aging is related to a reduced ability to attenuate an increase in cardiac output while experiencing heat stress (Minson et al. 1998). As the older men/women had a decreased ability to maintain stroke volume, their HR increased and relied on a higher percentage of HRR to increase cardiac output when the body experienced heat stress (Kenney et al. 2014).

Globally, the average age of outdoor workers is expected to increase from 37.3 years in 1986 to 42.3 years in 2026 (Lacey et al. 2017), and the proportion of workers aged over 55 is predicted to increase from 11.9% to 1994 to 24.8% in 2024 (Toossi 2015). Considering this trend, our results highlight that a differentiated heat adaptation strategy for older workers should be established. The current strategy has been applied equally to all outdoor workers based on the air temperature, regardless of each worker's age. The older workers may have a higher risk of heat strain occurrence even before air temperature reaches the level of implementing strategy. Therefore, they should protect themselves by drinking cool water and taking a break by checking their HR level just before HHS occurrence. These protective measures are possible with

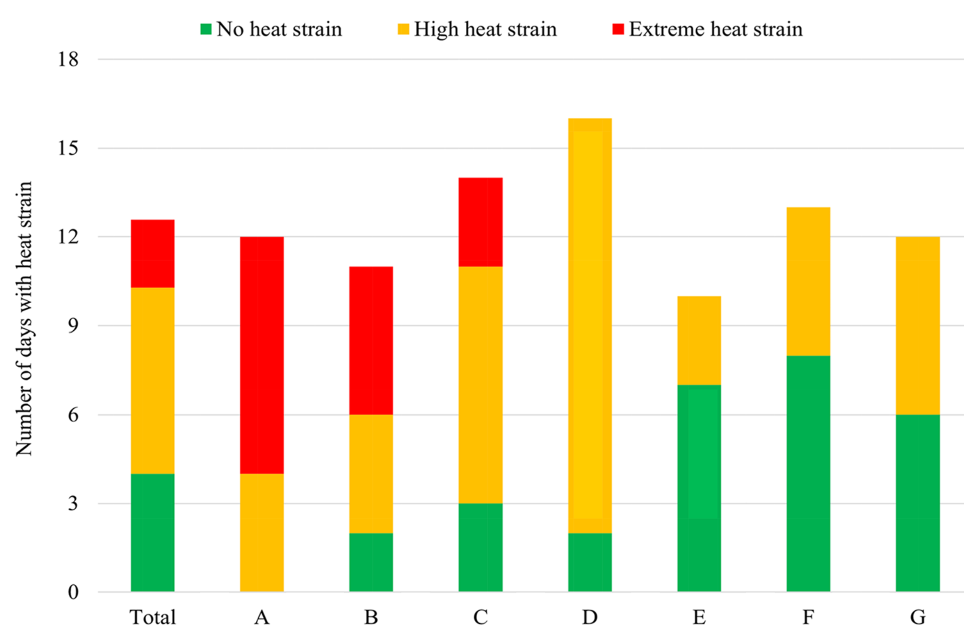

Fig. 7 Number of days with heat strain

Table 4 Result of stepwise regression analysis

Model	Unstandardized Coefficients		Standardized coefficients			
	B	Std. Error	Beta	t	Sig.	Adjusted R^2
Age	1.442	0.333	0.888	4.326	0.008	0.747
(Constant)	7.611	14.439		0.527	0.062	

the use of wearable sensors, such as a smartwatch, that can monitor their HRs.

3.4 Comparison Between Heat Strains and Thermal Comfort Levels

The survey questionnaire revealed that all the workers wore similar clothes (a cap and long pants with a long- or a short-sleeved shirt plus cool wristlets). Therefore, we excluded the influence of clothes on thermal comfort perception. The thermal comfort survey results showed different degrees of thermal comfort levels by different workers (Fig. 8). Workers A, B, and C voted the comfort level greater than 1, indicating that they perceived the overall thermal environments during the work as slightly comfortable. On the other hand, Workers D, E, F, and G voted the comfort level less than 0, which indicates slightly discomfortable.

To analyze the relationship between physiological heat strains and psychological comfort levels, we drew a quadrant graph with thermal comfort on the X-axis and HR on the Y-axis (Fig. 9). On the X-axis, the negative numbers indicated a thermally discomfortable state, and the positive numbers corresponded to a thermally comfortable one. On the Y-axis, we set two lines with the average HR corresponding to the HHS (blue line) and EHS (red line) occurrence, respectively. Hence, in the quadrant graph, the first and third quadrants were the dates of mismatch between physiological heat strains and psychological comfort levels, and the second and fourth quadrants were the match areas between the two.

We expected that the all-coordinate points would be marked on only the second or fourth quadrant because the psychological comfort level is generally proportional to physiological heat strain (Borg et al. 2015; Tikuisis et al. 2002). However, interestingly, some mismatches between heat strains and thermal comfort levels were observed (The 1st quadrant in Fig. 9). The all-coordinate points on the first quadrant belonged to Workers A, B, and C. This indicated that they felt thermally comfortable during their work despite heat strain occurrences. The main reason for the mismatches could be the longer work years of these participants as compared to the others. The average work year was 4.3 and 1.1 for Workers A, B, and C, and other workers, respectively, and the work year of Workers A, B, and C was about four times longer than that of other workers. As Workers A, B, and C were also older than other workers, in this study, work year was positively correlated with workers' age (Pearson correlation coefficient: 0.9, p-value <0.01). The work year tended to increase with age, which is in accord with the previous studies by Daher (2009). It was observed that the lower sensitivity of thermal comfort perception for outdoor workers experiencing more extended work with age increment due to thermal acclimatization would probably cause mismatches between heat strains and thermal comfort levels (Chung et al. 2015; Lam et al. 2021).

The unawareness of physiological heat strain could be dangerous for outdoor workers, especially when they are old. If workers feel thermally discomfortable while working, they can lower the heat strain by taking measures to protect themselves, such as drinking water or taking a break. However, they tend to continue working under a heat-exposed environment without the perception of heat strain. Consequently, heat strain increases further, thus leading to productivity decline and HRI incidences such as heat exhaustion and heatstroke. Therefore, we suggest a wearable sensor-based early-warning system considering personal characteristics, including outdoor workers' age and work years. They can wear a smart device to monitor their HRs, alerting them when their HR reaches HHS or EHS.

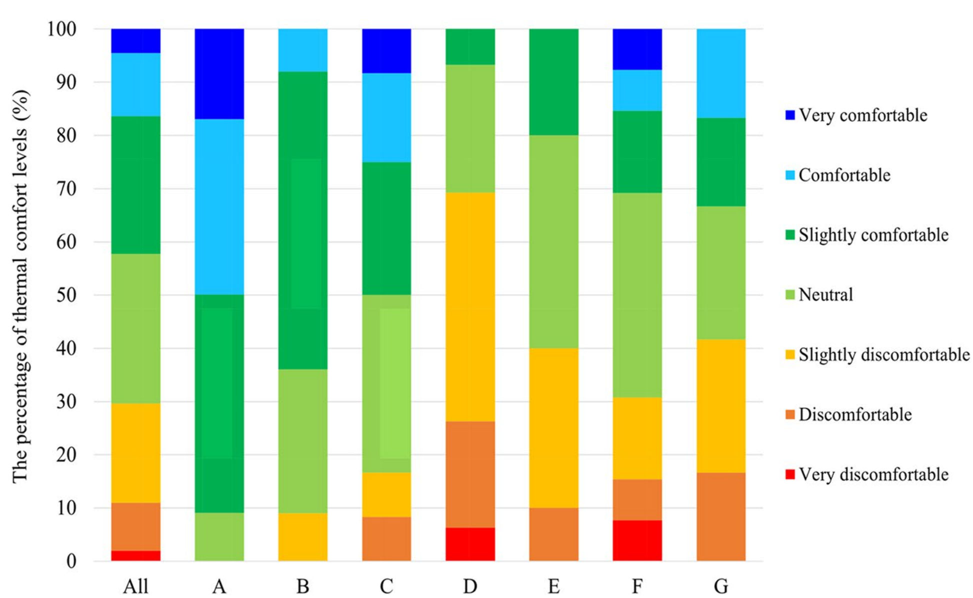

Fig. 8 Distribution of thermal comfort levels by each worker

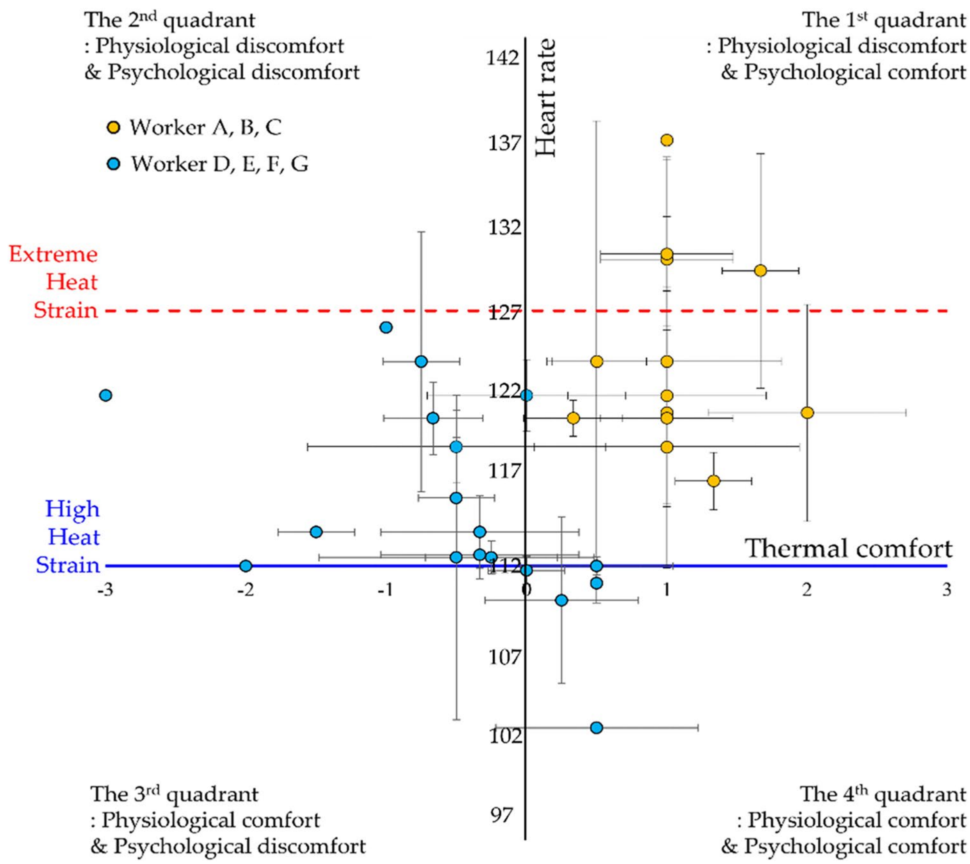

Fig. 9 Comparison between physiological heat strains and psychological thermal comfort levels

4 Conclusions

Heat stress from increasing heatwave intensity and frequency in summer causes economic losses by decreasing outdoor labor productivity and aggravates outdoor workers' health due to heat stress (IPCC 2022). To protect outdoor workers from heat strain and productivity decrease, an individual-based adaptation strategy should be set up considering the workplace's thermal environment and the personal characteristics of outdoor workers. We showed the possibility of on-site assessing outdoor workers' risk using a wearable sensor to measure the field's temperature and corresponding risk of physiological heat strain in a sample of outdoor workers. Our results suggest that the current government-led heatwave alarm system based on the official air temperature data over the entire metropolitan area should be revised using local data on a smaller municipal level or directly exposed temperature data of the workplace. Our results also demonstrate that older workers with a long work experience tend to perceive physiological heat strain as thermally comfortable despite heat strain occurrence. If these workers continue working under heat strains, they would be at high risk for heat-related illness or even death. Therefore, we propose a personalized self-adaptation strategy, such as an individual sensor-based early-warning system interconnecting a smartwatch with sensors. Although the sample size of participants was small (n = 7), this study will serve as a prototype for personalized heat wave risk assessment in Korea. Additionally, This study would help prepare a workplace data-driven guideline to update existing workplace heat prevention strategies and introduce more targeted high-temperature regulations for outdoor workers. If a government-led project that can recruit participants more systematically begins, it will be able to manage the climate change risk for outdoor workers much more safely.

Acknowledgements This work was financially supported by Korea Ministry of Environment (MOE) as "Graduate School specialized in Climate Change."

Data Availability The meteorological data used in the present study were taken from Korea Meteorological Administration, which is available in https://www.weather.go.kr/w/index.do (anyone can access the data through free registration).

Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

References

Acharya, P., Boggess, B., Zhang, K.: Assessing heat stress and health among construction workers in a changing climate: A review. Int. J. Environ. Res. Public. Health **15**, 247 (2018). https://doi.org/10.3390/ijerph15020247

Al-Bouwarthan, M., Quinn, M.M., Kriebel, D., Wegman, D.H.: A field evaluation of construction workers' activity, hydration status, and heat strain in the extreme summer heat of Saudi Arabia. Ann. Work Expo Health **64**, 522–535 (2020). https://doi.org/10.1093/annweh/wxaa029

American Conference of Governmental Industrial Hygienists (ACGIH). Threshold limit values for Physical Agents Documentation; Signature Publications: Cincinnati, OH (2007)

Bernard, T.E., Kenney, W.L.: Rationale for a personal monitor for heat strain. Am. Ind. Hyg. Assoc. J. **55**, 505–514 (1994). https://doi.org/10.1080/15428119491018772

Bernhard, M.C., Kent, S.T., Sloan, M.E., Evans, M.B., McClure, L.A., Gohlke, J.M.: Measuring personal heat exposure in an urban and rural environment. Environ. Res. **137**, 410–418 (2015). https://doi.org/10.1016/j.envres.2014.11.002

Borg, D.N., Stewart, I.B., Costello, J.T.: Can perceptual indices estimate physiological strain across a range of environments and metabolic workloads when wearing explosive ordnance disposal and chemical protective clothing? Physiol. Behav. **147**, 71–77 (2015). https://doi.org/10.1016/j.physbeh.2015.04.018

Borresen, J., Lambert, M.I.: The quantification of training load, the training response and the effect on performance. Sports Med. **39**, 779–795 (2009). https://doi.org/10.2165/11317780-000000000-00000

Cha, H.J., Lim, J.H.: The effect of urban road vegetation on a decrease of road surface temperature. J. Korean Inst. Lands Archit. **39**, 107–116 (2011). https://doi.org/10.9715/KILA.2011.39.3.107

Chan, A.P.C., Yang, Y.: Practical on-site measurement of heat strain with the use of a perceptual strain index. Int. Arch. Occup. Environ. Health **89**, 299–306 (2016). https://doi.org/10.1007/s00420-015-1073-7

Chung, J., Park, J., Cho, M., Park, Y., Kim, D., Yang, D., Yang, Y.: A study on the relationships between age, work experience, cognition, and work ability in older employees working in heavy industry. Phys. Ther. Sci. **27**, 1 (2015). https://doi.org/10.1589/jpts.27.155

Daher, W.S.: Age and experience: How do they correlate? Int. J. Knowl. Cult. Change Manag. **9**, 9 (2009). https://doi.org/10.18848/1447-9524/CGP/v09i09/49795

Deevi, B., Chundeli, F.A.: Quantitative outdoor thermal comfort assessment of street: A case in a warm and humid climate of India. Urban Clim. **34**, 100718 (2020). https://doi.org/10.1016/j.uclim.2020.100718

Duck, F.A.: Physical properties of tissues: a comprehensive reference book. Academic (2013)

Elitech: RC-5 Temperatue data logger manual. (2023). https://www.elitechlog.com/wp-content/manuals/RC-5.pdf Accessed 3 Mar 2023

Faurie, C., Varghese, B.M., Liu, J., Bi, P.: Association between high temperature and heatwaves with heat-related illnesses: A systematic review and meta-analysis. Sci. Total Environ. 158332 (2022). https://doi.org/10.1016/j.scitotenv.2022.158332

Gill, N., Sleivert, G.: Effect of daily versus intermittent exposure on heat acclimation. Aviat. Space Environ. Med. **72**, 385–390 (2001). https://doi.org/10.1580/1080-6032(2001)012[0215:AOCL]2.0.CO;2

Hashiguchi, N., Kodama, K., Lim, Y., Che, C., Kuroishi, S., Miyazaki, Y., Kobayashi, T., Kitahara, S., Tateyama, K.: Practical judgment of workload based on physical activity, work conditions, and worker's age in construction site. Sensors **20**, 3786 (2020). https://doi.org/10.3390/s20133786

Huang, T., Li, J., Xie, Y., Niu, J., Mak, C.M.: Simultaneous environmental parameter monitoring and human subject survey regarding outdoor thermal comfort and its modelling. Build. Environ. **125**, 502–514 (2017). https://doi.org/10.1016/j.buildenv.2017.09.015

Intergovernmental Panel on Climate Change (IPCC): Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Groups II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland (2022)

International Labor Organization: Working on a Warmer Planet: The Impact of Heat Stress on Labor Productivity and Decent Work. International Labor Organization, Geneva (2019)

Kenney, W.L., Craighead, D.H., Alexander, L.M.: Heat waves, aging, and human cardiovascular health. Med. Sci. Sports Exerc. **46**, 1891 (2014). https://doi.org/10.1249/MMS.0000000000000325

Korea Environment Institute (KEI): Report on Heatwave Impact. Sejong, Korea (2020)

Korea Occupational Safety and Health Agency (KOSHA). Study on a Comprehensive Measure of Health Protection for Outdoor Workers by Climate Change, Ulsan, Korea (2018)

Lacey, T.A., Toossi, M., Dubina, K.S., Gensler, A.B.: Projections overview and highlights, pp. 2016–2026. (2017). https://www.bls.gov/opub/mlr/2017/article/projections-overview-and-highlights-2016-26.htm. Accessed Oct 2017

Lam, C.K.C., Cui, S., Liu, J., Kong, X., Ou, C., Hang, J.: Influence of acclimatization and short-term thermal history on outdoor thermal comfort in subtropical South China. Energy Build. **231**, 110541 (2021). https://doi.org/10.1016/j.enbuild.2020.110541

Lee, Y., Yang, I., Kim, D.G., Lim, J.H.: A study on the factors affecting air temperature on roadside: Focusing on road conditions and traffic characteristics. KSCE J. Civ. Eng. Res. **33**, 1619–1629 (2013). https://doi.org/10.12652/Ksce.2013.33.4.1619

Logan, P.W., Bernard, T.E.: Heat stress and strain in an aluminum smelter. Am. Ind. Hyg. Assoc. J. **60**, 659–665 (1999). https://doi.org/10.1080/00028899908984488

Lunde, L.K., Koch, M., Veiersted, K.B., Moen, G.H., Waersted, M., Knardahl, S.: Heavy physical work: Cardiovascular load in male construction workers. Int. J. Environ. Health Res. **13**, 356 (2016). https://doi.org/10.3390/ijerph13040356

Matsuura, H., Mukaino, M., Otaka, Y., Kagaya, H., Aoshima, Y., Suzuki, T., Inukai, A., Hattori, E., Ogasawara, T., Saitoh, E.: Validity of simplified, calibration-less exercise intensity measurement using resting heart rate during sleep: A method-comparison study with respiratory gas analysis. BMC Sports Sci. Med. Rehabil. **11**, 27 (2019). https://doi.org/10.1186/s13102-019-0140-x

Minson, C.T., Wladkowski, S.L., Cardell, A.F., Pawelczyk, J.A., Kenney, W.L.: Age alters the cardiovascular response to direct passive heating. J. Appl. Physiol. **84**, 1323–1332 (1998). https://doi.org/10.1152/jappl.1998.84.4.1323open_in_new

Morabito, M., Messeri, A., Noti, P., Casanueva, A., Crisci, A., Kotlarski, S., Orlandini, S., Schwierz, C., Spirig, C., Kingma, B.R.M., Flouris, A.D., Nybo, L.: An occupational heat–health warning system for Europe: The HEAT-SHIELD platform. Int. J. Environ. Res. Public. Health **16**, 2890 (2019). https://doi.org/10.3390/ijerph16162890

Morris, N.B., Piil, J.F., Morabito, M., Messeri, A., Levi, M., Ioannou, L.G., Ciuha, U., Pogačar, T., Kajfež Bogataj, L., Kingma, B., Casanueva, A., Kotlarski, S., Spring, C., Foster, J., Havenith, G., Mayor, T.S., Flouris, A.D., Nybo, L.: The HEAT-SHIELD project—perspectives from an inter-sectoral approach to occupational heat stress. J. Sci. Med. Sport **24**, 747–755 (2021). https://doi.org/10.1016/j.jsams.2021.03.001

National Institute for Occupational Safety and Health (NIOSH): Criteria for a Recommended Standard: Occupational Exposure to Hot Environments. Department of Health and Human Services; Centers for Disease Control and Prevention (2016). https://www.cdc.gov/niosh/docs/2016-106/pdfs/2016-106.pdf?id=10.26616/NIOSHPUB2016106

Notley, S.R., Flouris, A.D., Kenny, G.P.: On the use of wearable physiological monitors to assess heat strain during occupational heat stress. Appl. Physiol. Nutr. Metab. **43**, 869–881 (2018). https://doi.org/10.1139/apnm-2018-0173

Park, J.G., Jung, W.S., Kim, E.B.: A study on the influence of extreme heat on daily mortality. J. Korean Soc. Atmos. Environ. **24**, 523–537 (2008). https://doi.org/10.5572/KOSAE.2008.24.5.523

Park, C.Y., Choi, Y.E., Kwon, Y.A., Kwon, J.I., Lee, H.S.: Studies on changes and future projections of subtropical climate zones and extreme temperature events over South Korea using high resolution climate change scenario based on PRIDE model. J. Korean Assoc. Reg. Geogr. **19**, 600–614 (2013)

Park, J., Pankratz, N.M.C., Behrer, A.P.: Temperature, workplace safety, and labor market inequality. SSRN Journal, Institute of Labor Economics (IZA): Bonn, 14560 (2021). https://doi.org/10.2139/ssrn.3892588

Parsons, K.: Occupational health impacts of climate change: Current and future ISO standards for the assessment of heat stress. Ind. Health **51**, 86–100 (2013). https://doi.org/10.2486/indhealth.2012-0165

Périard, J.D., Travers, G.J.S., Racinais, S., Sawka, M.N.: Cardiovascular adaptations supporting human exercise-heat acclimation. Auton. Neurosci. **196**, 52–62 (2016). https://doi.org/10.1016/j.autneu.2016.02.002

Pomerantz, M., Akbari, H., Chang, S.C., Levinson, R., Pon, B.: Examples of Cooler Reflective Streets for Urban Heat-Island Mitigation. Portland Cement Concrete and Chip Seals Lawrence Berkeley National Laboratory, California (2003). https://doi.org/10.2172/816205

Schlagbauer, D., Heck, D.: Is there a maximum age to be a construction worker? In Proceedings of the 19th CIB World Buildi ng Congress (1948). https://wbc2013.apps.qut.edu.au/papers/cibwbc2013_submission_202.pdf

Son, Y.T., Jeon, J.S., Whang, J.M.: Developing a model to predict road surface temperature using a heat-balance method, taking into traffic volume. J. Korea Inst. Intell. Transp. Syst. **14**, 30–38 (2015). https://doi.org/10.12815/kits.2015.14.2.030

Spagnolo, J., De Dear, R.: A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia. Build. Environ. **38**, 721–738 (2003). https://doi.org/10.1016/S0360-1323(02)00209-3

Synnefa, A., Karlessi, T., Gaitani, N., Santamouris, M., Assimakopoulos, D.N., Papakatsikas, C.: Experimental testing of cool colored thin layer asphalt and estimation of its potential to improve the urban microclimate. Build. Environ. **46**, 38–44 (2011). https://doi.org/10.1016/j.buildenv.2010.06.014

Tanaka, H., Monahan, K.D., Seals, D.R.: Age-predicted maximal heart rate revisited. J. Am. Coll. Cardiol. **37**, 153–156 (2001). https://doi.org/10.1016/s0735-1097(00)01054-8

Tikuisis, P., Mclellan, T.M., Selkirk, G.: Perceptual versus physiological heat strain during exercise-heat stress. Med. Sci. Sports Exerc. **34**, 1454–1461 (2002). https://doi.org/10.1097/00005768-200209000-00009

Toossi, M.: Labor Force Projections to 2024. The labor force is growing, but slowly (2015). https://www.bls.gov/opub/mlr/2015/article/labor-force-projections-to-2024.htm. Accessed Dec 2015

TOPIS Seoul (2022). https://topis.seoul.go.kr/. Accessed Aug 2022

Uejio, C.K., Morano, L.H., Jung, J., Kintziger, K., Jagger, M., Chalmers, J., Holmes, T.: Occupational heat exposure among municipal workers. Int. Arch. Occup. Environ. Health **91**, 705–715 (2018). https://doi.org/10.1007/s00420-018-1318-3

von Scheidt, F., Meier, S., Krämer, J., Apitz, A., Siaplaouras, J., Bride, P., Kaestner, M., Apitz, C.: Heart rate response during treadmill exercise test in children and adolescents with congenital heart disease. Front. Pediatr. **7**, 65 (2019). https://doi.org/10.3389/fped.2019.00065

Watts, N., Amann, M., Ayeb-Karlsson, S., Belesova, K., Bouley, T., Boykoff, M., Byass, P., Cai, W., Campbell-Lendrum, D., Chambers, J., Cox, P.M., Daly, M., Dasandi, N., Davies, M., Depledge, M., Depoux, A., Dominguez-Salas, P., Drummond, P., Ekins, P., Flahault, A., Frumkin, H., Georgeson, L., Ghanei, M., Grace, D., Graham, H., Grojsman, R., Haines, A., Hamilton, I., Hartinger, S., Johnson, A., Kelman, I., Kiesewetter, G., Kniveton, D., Kiang, L., Lott, M., Lowe, R., Mace, G., Sewe, M.O., Maslin, M., Mikhaylov, S., Milner, J., Latifi, A.M., Moradi-Lakey, M., Morrissey, K., Murray, K., Neville, R., Nilsson, M., Oreszczyn, T., Owfi, R., Rencheon, D., Pye, S., Rabbaniha, M., Robinson, E., Rocklöv, J., Schütte, S., Shumake-Guillemot, J., Steinbach, R., Tabatabaer, M., Wheeler, N., Wilkinson, P., Gong, P., Montgomery, H., Costello, A.: The Lancet countdown on health and climate change: From 25 years of inaction to a global transformation for public health. Lancet **391**, 581–630 (2018). https://doi.org/10.1016/S0140-6736(17)32464-9

WorldData.info (2023). https://www.worlddata.info/. Accessed Aug 2019

World Health Organization: A healthy lifestyle – WHO recommendations (2010). https://www.who.int/europe/news-room/fact-sheets/item/a-healthy-lifestyle---who-recommendations. Accessed 6 May 2010

World Health Organization. Constitution of the World Health Organization Entered Into Force on April 7th; World Health Organization: Geneva (1948). https://apps.who.int/gb/bd/PDF/bd47/EN/constitution-en.pdf?ua=1

Yi, W., Chan, A.P.C., Wang, X., Wang, J.: Development of an early-warning system for site work in hot and humid environments: A case study. Autom. Constr. **62**, 101–113 (2016). https://doi.org/10.1016/j.autcon.2015.11.003

Yun, K.S., Heo, K.Y., Chu, J.E., Ha, K.J., Lee, E.J., Choi, Y., Kitoh, A.: Changes in climate classification and extreme climate indices from a high-resolution future projection in Korea. Asia-Pacific J. Atmos. Sci. **48**, 213–226 (2012). https://doi.org/10.1007/s13143-012-0022-6

Zeng, W., Wan, X., Lei, M., Gu, G., Chen, T.: Influencing factors and prediction of arsenic concentration in Pteris vittata: A combination of geodetector and empirical models. Environ. Pollut. **292**, 118240 (2022). https://doi.org/10.1016/j.envpol.2021.118240