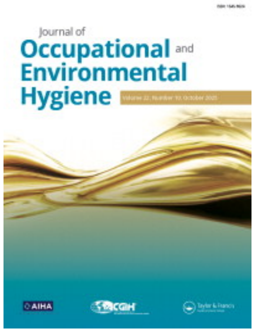

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Heat stress and strain in commercial construction workers in the summer: A pilot study

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ABSTRACT

Construction workers are 13 times more likely to die from heat-related illnesses than workers in other job industries. This elevated risk is attributed to excessive heat stress from environmental exposure, metabolic heat generated from physical labor, and the insulating effects of protective clothing. Levels of heat stress may vary across job types, reflecting the diversity of tasks performed and the work environment. Despite elevated risks, heat strain assessed by core temperature (Tcore) in construction workers during summertime in the United States has not been evaluated previously. Thirty-two construction workers (three females) were monitored over 3 summer workdays. Participants were categorized by job type (carpenter, concrete, laborer, roofer) and work environment (covered, uncovered). Heat index (HI), heart rate (HR), and Tcore were measured throughout the workday, while hydration was assessed through pre- and post-shift measurements of urine specific gravity (USG). Peak HI over the 3 days was 27.3, 35.2, and 33.7 °C, indicating the potential for low to moderate heat stress. Roofers experienced a higher peak HI compared to other job types ($p < 0.01$), but no differences were observed between workers in covered (28.8 ± 3.7 °C) and uncovered (32.1 ± 4.2 °C) areas ($p = 0.37$). The estimated peak metabolic rate was higher in workers in uncovered areas (868 ± 238 W) compared to covered (632 ± 130 W) ($p < 0.01$), with no differences among job types ($p = 0.23$). Forty-three percent of workers had Tcore exceeding 38.0 °C, with 4% exceeding 38.5 °C. Based on USG, 63% of workers began work dehydrated (1.022 ± 0.005), but urine did not become more concentrated during the workday (post-shift USG; 1.022 ± 0.007) ($p = 0.78$). Forward stepwise regression identified that peak metabolic rate plus post-shift USG were the combined variables most associated with peak Tcore ($r^2 = 0.55$, $p < 0.01$). Construction workers, even in low to moderate environmental heat exposure, experienced significant heat strain, primarily due to an elevated metabolic rate. Environmental heat exposure and metabolic rate vary by job type and work environment.

KEYWORDS
Core temperature; heat illness; hydration; worker safety; hyperthermia; dehydration; heat index; occupational heat stress

Introduction

Construction work is characterized by prolonged physical work resulting in high metabolic activity (Poulianiti et al. 2019). Workers perform a wide range of tasks, including roofing, pouring concrete, laying bricks, and glazing, that vary in their demands. For example, bricklayers often engage in lifting moderate to heavy loads and handle bricks or blocks for 35 to 60% of their working time (Boschman et al. 2011), while roofers are crawling, squatting, stooping, and kneeling for over 75% of their work time (Breloff et al. 2019; Wang et al. 2017).

In addition to varying physical demands, construction workers are frequently exposed to unfavorable environmental conditions, ranging from working outdoors exposed to high air temperatures, relative humidity, and/or solar radiation to enclosed spaces with limited airflow. These conditions become more severe during the summer months when environmental heat exposure increases, elevating the risk of heat-related illnesses. Previous studies have shown that construction workers have a 13 times higher risk of heat-related deaths than workers in other sectors (Gubernot et al. 2015). Despite constituting

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only 6% of the total workforce, construction workers accounted for 36% of all occupational heat-related deaths for the period between 1992 and 2016 (Dong et al. 2019), with the highest risks in cement masons, roofers, helpers, brick masons, and construction laborers (Dong et al. 2019).

The latest climate projections indicate that global temperatures will continue to rise and heat waves (defined as extended periods of unusually high atmospheric heat stress) will increase in frequency, intensity, and duration (EPA 2021). This is evidenced by data collected by the National Oceanic and Atmospheric Administration (NOAA 2021) in the United States (US), which has reported that heat waves are occurring more often, from an average of two heat waves per year during the 1960s to six per year during the 2010s. Also, the annual number of days over 37.8 °C is projected to double, and days over 40.6 °C are projected to triple by 2100 compared to a 1971 to 2000 baseline (Dahl et al. 2019). These increased environmental temperatures will affect regions in the U.S., but certain regions, such as the Midwest, Southwest, and Southeast, will be affected to a greater degree (NOAA 2021). High environmental temperatures have serious impacts on the health of many populations, particularly those involved in physically demanding occupational activities, such as construction workers (Park et al. 2017).

Prolonged work in high environmental temperatures may induce hyperthermia, dehydration, and fatigue, which are indicative of heat strain—the physiological response of the body to heat stress. Heat stress refers to the combined effect of environmental factors (e.g., air temperature, humidity, air flow, and radiant heat), metabolic heat generated from physical labor, hydration status, and the insulating properties of clothing. When heat stress exceeds the body's ability to dissipate heat, it increases the risk of heat-related illnesses (Binazzi et al. 2019; Flouris et al. 2018). For worker safety, the ACGIH® recommends monitoring heat strain by maintaining core temperature (Tcore) within +1.0 °C for the average person or a threshold value of 38.0 °C for baseline Tcore of 37.0 °C, and a threshold of 38.5 °C for acclimatized workers (ACGIH 2024). Surprisingly, no studies have quantified heat stress and strain among construction workers in the U.S. (Chapman et al. 2021). Therefore, this pilot study aimed to measure heat stress and physiological heat strain in commercial construction workers during work in summer.

Methods

Subject recruitment

A 3-day observational pilot study was conducted at a commercial construction site located in Missouri, U.S., during July of 2023 (summer season). A convenience sample of 32 construction workers (29 males and three females) was recruited at the construction site. Workers were recruited via word of mouth throughout the construction site, and management introduced study information to workers. Interested participants were then encouraged to meet with the research team for further details. The protocol and procedures were approved by the University of New Mexico's institutional review board (protocol #2208012352). Before data collection, workers were presented with details of the study, and their informed consent was obtained. During screening, height, weight, and blood pressure were measured and recorded. Participants were excluded if: their resting blood pressure was greater than 140/90 mmHg, they were currently diagnosed with any disease, taking any medications known to impair muscle metabolism or thermoregulatory responses, diagnosed with a bleeding or blood clotting disorder, had a physical injury or limitations, or were under a medical provider's care for any condition that may interfere with their safe participation in the study. Females were excluded if they were pregnant. To reduce the impact of a day of rest before each work shift, data were collected Tuesday through Thursday (workers typically worked Monday through Friday).

Workers were asked about their job duties and categorized into four job groups: carpenters ($n = 6$), concrete workers ($n = 13$), laborers ($n = 8$), and roofers ($n = 5$). The job site was large, with the foundations for two buildings in place, each consisting of three levels. The bottom two levels were semi-enclosed with no air conditioning and large openings on the sides of the building to allow machinery to enter and exit, resulting in a similar ambient air temperature to the outside. Due to the variety of job demands in construction, some workers worked outside while many were inside the semi-enclosed buildings. Therefore, participants were also classified by work environment, independent of job type, into two categories: covered ($n = 24$) was defined as within the open-air environment without direct exposure to sunlight, or uncovered ($n = 8$), which was defined as an open-air environment with mostly direct exposure to sunlight. During the study, participants were instructed to maintain their typical work-related activities and routines. Each worker was sampled only once in the course of this 3-day study.

Work shift data collection

Participants arrived at work approximately 30 min early to meet with researchers for pre-shift measurements at a location on the worksite designated for data collection. Workers began their shifts between 3:30 and 5:30 AM. During this pre-shift period, nude body weight was measured with a scale, and a urine sample was collected to assess hydration via urine-specific gravity (USG) with a manual refractometer (Cole-Parmer, RSA-BR90A, Vernon Hills, IL). To maintain privacy, the scale was placed in a large restroom within a trailer on the job site, and the monitor displaying the body weight was outside of the restroom with a member of the research team recording the weight. Participants were then equipped with an iButton sensor (model DS1921H, Embedded Data Systems, KY) taped to the chest (halfway between the anterior line and nipple for men, and one-third of the distance between the anterior axillary line and the nipple for women) to measure chest skin temperature and a Polar chest strap (Polar H10, Polar Electro Inc., Lake Success, NY) to continuously record heart rate throughout the work shift. A Tcore measuring capsule (BodyCap, e-Celsius, Caen, France) was then ingested to continuously record gastrointestinal temperature (used as Tcore) during the work shift. Following the completion of the pre-shift data collection and instrumentation, participants began work as they normally would.

Environmental conditions were quantified by continuously measuring dry bulb and globe temperatures and relative humidity using heat stress monitors at covered (QUESTemp QT-44, TSI QUESTemp, Shoreview, MN) and uncovered (Kestrel 4400 Heat Stress Tracker, Nielsen-Kellerman, Boothwyn, PA) locations near the workers. Due to equipment malfunction, the Kestrel equipment did not consistently record globe temperature measurements. Thus, wet bulb globe temperature (WBGT) is only reported for the covered working environment. To compare the environmental conditions between work environments, the heat index (HI) was also reported. To this end, it is important to note that the Occupational Safety and Health Administration (OSHA) currently uses the HI to classify the potential risks associated with heat stress (OSHA 2022). As such, the thresholds for HI indicated by the OSHA Heat Safety Tool App were used to classify heat stress (Caution less than 26.7 °C HI; Warning between 26.7 and 34.9 °C HI; and Danger at 35.0 °C HI or greater) (OSHA 2022).

At the end of the shift, participants returned to the designated data collection area to provide a urine sample to measure post-shift USG, and nude body weight was measured again. As a marker of hydration, the change in body weight was later calculated as a percent change relative to pre-shift nude body weight (Casa et al. 2000). Food and drink consumption were not accounted for when assessing change in body weight. Researchers then asked participants about their average and maximal rating of perceived exertion (RPE) (Borg 1982) during that work shift and their average and maximal thermal discomfort (1-comfortable, 5-intolerable), adapted from a scale by Gagge et al. (1967). These perceptual scales were administered at the end of the day rather than during the shift due to the logistics of the large jobsite, which did not allow the research team to obtain these measures during the work shift.

Data cleaning for heat index, heart rate, and core temperature

Both the Kestrel and Quest devices measure environmental conditions and record data every minute, which is later averaged over 30-min periods. Peak HI is reported as the highest value of these 30-min periods. The respective devices monitoring Tcore and heart rate also recorded data at 1-min intervals, but data for these variables was later averaged over 5-min periods. Before averaging, reported values of zero and erroneous values (any point that changed $\geq$ 0.5 °C from the previous minute) were removed from the dataset. The majority of Tcore data that was removed was from the first 2 hr, where the capsule was likely located within the stomach, and more sensitive to changes in temperature from ingestion of food or drink. The peak values for Tcore were defined as the highest 5-min value for each worker.

Metabolic rate and heat stress Limit Value calculations

Metabolic rate (M) was estimated from heart rate (Malchaire et al. 2017) and adjusted for increases in Tcore (Bröde and Kampmann 2019) using standard equations (equations 1–10). Maximal heart rate (HR_{max}) was estimated using the Tanaka equation (equation 1) (Tanaka et al. 2001). Body surface area (A_b) was calculated (equation 2) (Du Bois and Du Bois 1989) and used to estimate resting metabolic rate

(M_0) (equation 3) (Malchaire et al. 2017). An estimate of maximal work capacity (MWC) was calculated from age and body weight (equation 4) (Malchaire et al. 2017). Then, the metabolic rates were calculated for each participant using heart rate sampled over 5-min periods (HR_{wm}), the estimates for maximal heart rate, resting metabolic rate, and maximal work capacity (equation 5). Resting heart rate (HR_0) was calculated as the first percentile of heart rate recorded during the working time (equation 6) (Malchaire et al. 2017).

$$HR_{max}(bpm) = 208 - 0.7 \times age\,(yr)\ \text{beats per minute (bpm)} \quad (1)$$

$$A_b(m^2) = 0.007188 \times \text{Weight (kg)}^{0.425} \times \text{Height (m)}^{0.725} \quad (2)$$

$$M_0(W) = 60 \times A_b(m^2) \quad (3)$$

$$MWC = 19.45 - (0.133 \times \text{Age (yr)} \times \text{Weight (kg)}) \quad (4)$$

$$M\ (W) = \frac{MWC\ (W) - M_0\ (W)}{HRmax\ (bpm) - HR_0\ (bpm)} (HRwm\ (bpm) - HR0\ (bpm)) + M0\ (W) \quad (5)$$

$$HR_0(bpm) = \text{the first percentile of heart rate measurements observed (bpm)} \quad (6)$$

$$\dot{V}O_2(mL/kg/min) = M\ (W)/5.68/60 \quad (7)$$

$$Q10\ (\text{correction factor}) = 2 - (2.1^{(Tcore\ (^\circ C) - 36.8)/10)}) \quad (8)$$

$$\dot{V}O_2 - \text{Tcore corrected}\ (mL/kg/min) = \dot{V}O_2(mL/kg/min) \times Q10 \quad (9)$$

$$M - \text{Tcore corrected}(W) = \dot{V}O_2 - \text{Tcore corrected}\ (mL/kg/min) \times 60 \times 5.68 \quad (10)$$

Oxygen consumption ($\dot{V}O_2$) was then estimated from metabolic rate (equation 7) (Bröde and Kampmann 2019). The resulting oxygen consumption estimates were corrected to adjust for the effect of elevations in Tcore on metabolism (i.e., the Q10 effect) (equation 9) by multiplying the obtained $\dot{V}O_2$ by the Q10 coefficient (equation 8) (Bröde and Kampmann 2019; Kampmann and Bröde 2015). The oxygen consumption data were converted to units of metabolism (Watts) (equation 10). The peak metabolic rate was defined as the highest estimated metabolic rate over 5-min for each worker. Peak and average metabolic rates were also classified in accordance with ACGIH (2024) criteria for work intensity including "Rest" (<115 W), "Light" (115 to 235 W), "Moderate" (235 to 360 W), "Heavy" (360 to 470 W), and "Very heavy" (>470 W). Data were used from the entirety of the workday, including breaks. Peak and average heart rate are presented as absolute values and as a percentage of estimated maximal heart rate.

To better understand the combined effects of metabolic and environmental heat exposures, the measured WBGT values in the covered work environment were compared to Action Limit (AL) and Threshold Limit Value (TLV®) occupational exposure limit values published by the ACGIH (2024).

$$AL\ (^\circ C) = 59.9 - 14.1\ \log_{10} M\ (W) \quad (11)$$

$$TLV\ (^\circ C) = 56.7 - 11.5\ \log_{10} M\ (W) \quad (12)$$

The AL is the threshold of combined metabolic and environmental heat that healthy unacclimatized workers should not surpass to reduce the risk of heat illness, and was calculated as (Equation 9). The TLV is a higher threshold, as it was made for acclimatized workers (equation 10). To calculate these values, the estimated metabolic rate was averaged over 30-min and entered into these equations. The resultant values were then compared to the measured WBGT values recorded in the covered work environment. Results are reported as the percentage of time the measured WBGT was above the AL and TLV for the corresponding metabolic rate.

Statistical analyses

One-way analysis of variance (ANOVA) was conducted using the Brown-Forsythe and Welch tests to compare mean values by job type (carpenter, concrete, etc.) for the following variables: average and peak Tcore, average and peak percentage heart rate max, RPE, thermal discomfort, metabolic rate, change in body weight, chest skin temperature, and heat index. Significant differences were further explored by using Dunnett's T3 multiple comparison test. Unpaired t-tests were conducted to compare mean values at covered or uncovered locations for the same variables. Mixed-effects models, using a random effect for individuals, were conducted to assess differences in USG based on timepoint (pre- and post-shift), job type, and work environment.

To determine significant correlates of peak Tcore, nine variables (age, BMI, mean thermal discomfort, peak HI, percent change in body mass, pre- and post-shift USG, peak chest skin temperature, and peak calculated metabolic rate) were assessed using a forward stepwise regression model with an entry and exit α of $p < 0.05$. Statistical significance for all analyses was set at $p \leq 0.05$. All statistical analyses were completed using GraphPad Prism 9.4 (GraphPad Software Inc., La Jolla, CA, USA).

Results

Subject characteristics

Anthropometric measures of the 32 workers assessed can be found in Table 1. In general, there was a large variability in age, ranging from 18 to 64 yr.

Environmental conditions

During the 3 days of data collection, the average measured peak HI across all work environments was 30.4 ± 4.0 °C. Due to excessive rain, workers in the uncovered environment were called off work and were not assessed during the first day of data collection. By day (Tues, Wed, and Thurs), peak HI values in the covered environment were 24.7, 32.0, and 29.6 °C respectively, with the first day considered to be in the "caution" risk level according to OSHA and the second and third being in the "warning" category (OSHA 2022). The days for uncovered work had peak HI values of 27.3, 35.2, and 33.7 °C, respectively, with the second day being in the "danger" risk category and days one and three being classified in the "warning" risk level. The average HI across all work environments was 27.8 ± 3.9 °C. Mean HI, dry-bulb temperature, relative humidity, in the covered and uncovered work environments, and WBGT in covered areas only over the 3 days of data collection can be found in Table 2. There was no difference in peak HI between covered (28.8 ± 3.7 °C) and uncovered (32.1 ± 4.2 °C) areas ($p = 0.37$). Concrete workers were exposed to a significantly lower peak HI (27.5 ± 3.7 °C) than either carpenters (32.5 ± 1.6 °C, $p < 0.01$) or roofers (34.6 ± 0 °C, $p < 0.01$). Additionally, roofers were exposed to a higher peak HI than laborers (29.6 ± 0.0 °C, $p < 0.01$). A visual graphic of the dry bulb, HI, and WBGT values for each day and work environment by work time can be found in Figure 1A–E.

Metabolic work and heat strain

Both peak and mean metabolic rate for the duration of the workday were calculated for 25 of 32 workers. Seven workers were not included because the continuous recording of heart rate was inconsistent, or there was a lack of Tcore data. The average peak metabolic rate calculated was "very heavy" at 707 ± 201 W, with a mean metabolic rate of 380 ± 89 W, corresponding to a "heavy" work intensity. All job types had an average peak metabolic rate corresponding to "very heavy"

Table 1. Anthropometric measures of construction workers by job type.

Variables	Carpenters ($n = 6$)	Concrete ($n = 13$)	Laborers ($n = 8$)	Roofers ($n = 5$)	Total ($N = 32$)
Age (yr)	33 ± 13	35 ± 12	37 ± 14	43 ± 13	36 ± 13 (18–64)
Sex	6 M	12 M	5 M / 3 F	5 M	29 M/3 F
Height (cm)	176 ± 9	175 ± 11	170 ± 12	174 ± 3	174 ± 10 (148–192)
Body weight (kg)	85.1 ± 24.3	86.0 ± 14.0	77.5 ± 14.1	90.1 ± 18.5	84.3 ± 16.7 (56.8–120.5)
BMI (kg/m^2)	27.2 ± 5.6	28.3 ± 4.5	26.9 ± 4.5	29.7 ± 5.7	28.0 ± 4.8 (18.3–35.3)
Systolic BP (mmHg)	122 ± 8	122 ± 9	120 ± 8	123 ± 9	122 ± 8 (102–135)
Diastolic BP (mmHg)	75 ± 9	76 ± 6	73 ± 8	78 ± 6	75 ± 7 (60–88)

Note: Data presented as mean ± standard deviation (minimum, maximum), M = male, F = female, BMI = Body mass index, BP = blood pressure.

Table 2. Environmental conditions by day and work environment.

	Covered			Uncovered		
	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3
HI (°C)	24.0 ± 0.5 (23.0–24.7)	28.9 ± 2.9 (23.3–32.0)	28.8 ± 0.4 (28.3–29.6)	23.1 ± 1.7 (21.5–27.3)	30.3 ± 4.8 (22.1–35.2)	30.3 ± 2.4 (24.9–33.7)
Dry-bulb (°C)	22.9 ± 0.3 (22.5–23.5)	25.5 ± 1.9 (22.0–27.5)	26.3 ± 1.1 (24.8–27.8)	22.2 ± 1.2 (21.0–24.5)	26.8 ± 3.0 (21.2–29.7)	28.2 ± 2.4 (23.2–31.4)
RH (%)	77 ± 2 (74–81)	89 ± 3 (84–95)	76 ± 15 (57–94)	85 ± 8 (62–99)	79 ± 9 (70–94)	64 ± 17 (45–96)
WBGT (°C)	21.1 ± 0.2 (20.7–21.6)	24.5 ± 1.6 (21.8–26.1)	24.0 ± 0.4 (23.3–24.6)			

Note: Data presented as mean ± standard deviation (minimum-maximum), HI = heat index, RH = relative humidity, WBGT = wet bulb globe temperature.

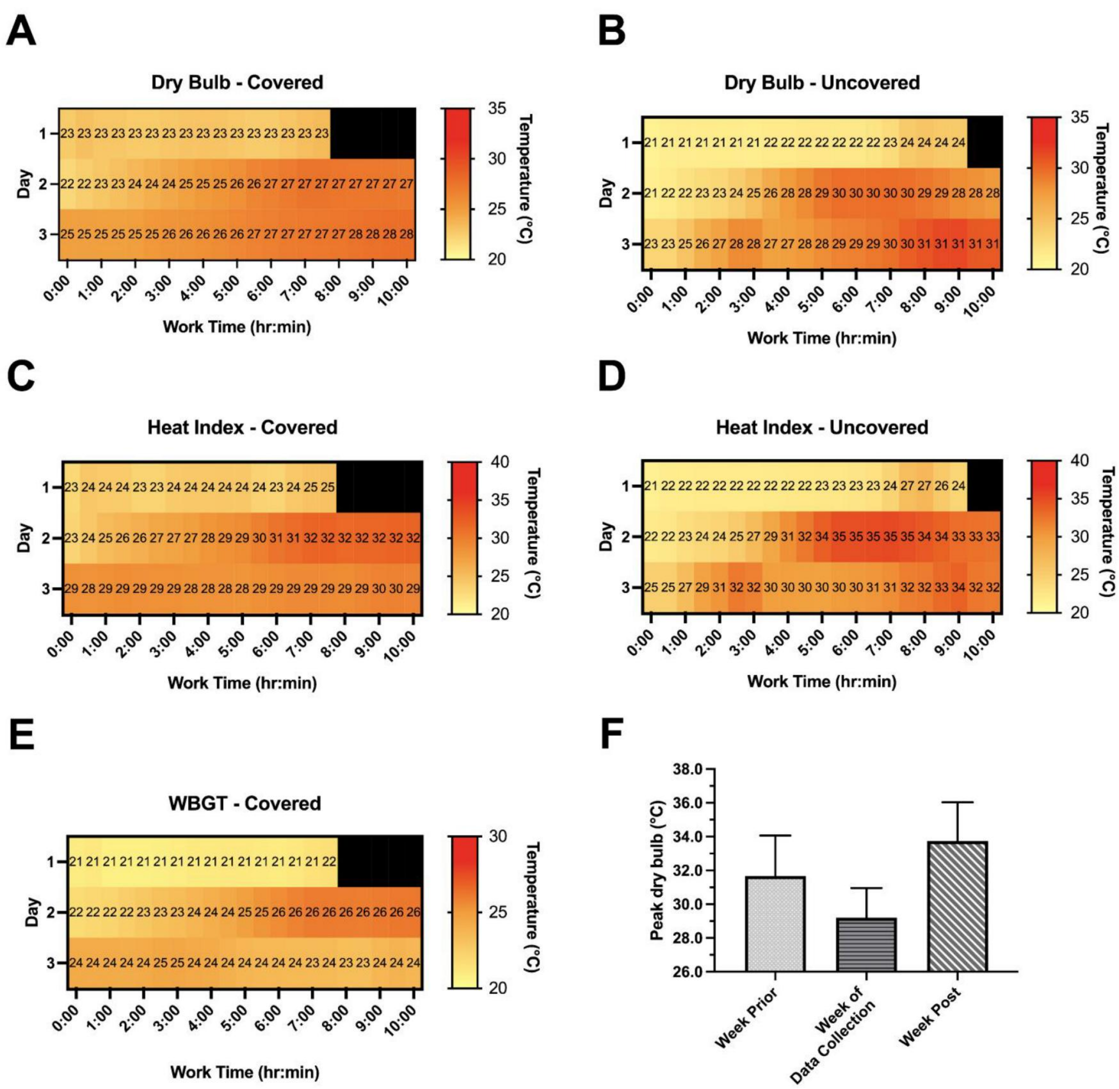

Figure 1. Environmental conditions during the work shift by day (A–E). Data are presented as dry bulb temperature by every 30 min of work time in covered (A) and uncovered (B) work environments, heat index in covered (C) and uncovered (D) work environments, and wet bulb globe temperature (WBGT) (E) in the covered work environment. Mean and standard deviation of peak dry bulb temperature by week are presented in (F). Created with GraphPad prism.

Table 3. Heart rate and estimated metabolic rate in construction workers by job type ($N = 25$).

Variables	Carpenter ($n = 4$)	Concrete ($n = 10$)	Laborer ($n = 6$)	Roofer ($n = 5$)	Total ($N = 25$)
Peak HR (% of max)	68 ± 9	68 ± 4	64 ± 6	77 ± 9	69 ± 8
Mean HR (% of max)	49 ± 4	51 ± 3	50 ± 6	58 ± 8	52 ± 6
Peak HR (bpm)	127 ± 21	127 ± 11	118 ± 12	137 ± 20	127 ± 17
Mean HR (bpm)	92 ± 12	96 ± 7	92 ± 10	104 ± 18	96 ± 11
Peak MR (W)	808 ± 258	710 ± 110	510 ± 48	845 ± 276	707 ± 201
Mean MR (W)	424 ± 123	391 ± 57	292 ± 26	432 ± 102	380 ± 89

Note: Data presented as mean ± standard deviation. No significant differences among job types ($p > 0.05$).
HR = heart rate, MR = metabolic rate.

work, but there were no significant differences in this general classification observed among job types (Table 3) ($p = 0.11$). However, workers in uncovered spaces (868 ± 238 W, $n = 17$) had a significantly higher peak work rate than workers in covered areas (632 ± 130 W, $n = 8$) ($p < 0.01$). Similarly, there were no significant differences in mean calculated metabolic rate among job types (Table 3) ($p = 0.09$); however, uncovered workers (445 ± 96 W, "heavy") had a significantly higher average calculated metabolic rate than covered workers (349 ± 68 W, "moderate") ($p = 0.01$). To better understand the combined metabolic and environmental heat stress, measured WBGT in the covered work environment was compared to

AL and TLVs for the 17 workers whose metabolic rate could be calculated. In total, 25.1% of the time working was greater than the AL (Day 1, 6.3%; Day 2, 55%; Day 3, 14.4%), while only 3.3% exceeded the TLV (Day 1, 0%; Day 2, 10%; Day 3, 0%). There was no difference among job types in average ($p = 0.29$) or peak ($p = 0.34$) percent of heart rate max, presented in Table 3. Peak percentage heart rate max was significantly higher in the uncovered (74.4% ± 10.7%) compared to covered (66.3% ± 5.4%) workers ($p = 0.02$). Similarly, the average percentage heart rate max was higher for uncovered (55.5% ± 7.5%) than covered (50.6% ± 4.4%) ($p = 0.05$).

Tcore was assessed in 28 of 32 workers, with four workers not being assessed due to the unavailability of Tcore capsules. Average Tcore throughout the work shift was 37.4 ± 0.4 °C (Figure 2C), with the average peak Tcore being 37.9 ± 0.3 °C. As seen in Figure 2A and B, there were no significant differences in peak Tcore among job types ($p = 0.51$), but workers in uncovered areas (38.1 ± 0.3 °C) had significantly higher peak Tcore than covered (37.8 ± 0.2 °C) workers ($p = 0.04$). Only one roofer experienced a Tcore exceeding 38.5 °C, while three out of five roofers (60%) experienced peak Tcore greater than 38.0 °C. Additionally, five out of eight (63%) workers in uncovered areas recorded a peak Tcore greater than 38.0 °C, while only seven out of 20 (35%) workers in covered areas reached this threshold. Four percent of all workers reached a peak Tcore greater than 38.5 °C, while 43% reached a peak Tcore greater than 38.0 °C.

Chest skin temperature

The average peak chest skin temperature among the 32 workers was 35.2 ± 1.4 °C. A significant difference in peak chest skin temperature (Figure 2D) was observed by job type ($p = 0.01$), with post-hoc tests revealing that concrete workers (34.2 ± 1.6 °C) had a significantly lower peak chest skin temperature than carpenters (35.8 ± 0.6 °C) ($p = 0.03$), laborers (35.9 ± 0.8 °C) ($p = 0.01$), and roofers (36.0 ± 0.8 °C) ($p = 0.04$). There were no other significant differences among job types (>0.05). Additionally, it was found that peak chest skin temperature was higher in uncovered workers (36.0 ± 0.6 °C) than in covered workers (Figure 2E) (35.0 ± 1.4 °C) ($p = 0.04$).

Hydration

There was no significant effect of time in USG from pre- (1.022 ± 0.005) to post-shift (1.022 ± 0.007) ($p = 0.78$). Additionally, there was no effect of job type (Figure 3A) ($p = 0.33$) or interaction among job types and time of measurement ($p = 0.97$). Similarly, there was no effect of work environment (Figure 3B) ($p = 0.31$) or interaction between work environment and time ($p = 0.14$). Interestingly, at both the pre- and post-shift timepoints, 20 out of 32 workers (63%) had a USG greater than 1.020, considered a threshold for dehydration (Cheuvront et al. 2010). There was an average decrease in body weight of 1.1% ± 0.9% from pre- to post-shift. There were no significant differences in body weight change between groups based on job type (Figure 3C) ($p = 0.25$) or work conditions (Figure 3D) ($p = 0.13$). It is worth noting that of the 32 workers, five (16%) lost greater than 2.0% body weight throughout the work shift, a commonly used threshold to indicate significant dehydration (Institute of Medicine 2005). Three of the workers were roofers and two were concrete workers, making up 60% and 15% of each job type, respectively. It is important to note that water and frozen popsicles were freely available for workers in large quantities throughout all work areas at the job site.

Perception of exertion and thermal discomfort

Table 4 presents maximal and mean RPE and thermal discomfort values, categorized by job type and as combined totals. The maximal RPE for all workers was 13.7 ± 3.4, corresponding to a perceived exertion of "somewhat hard." Maximal RPE did not significantly differ by job type ($p = 0.11$) or work condition ($p = 0.15$). The average RPE for all workers was 11.5 ± 2.8, indicating a perceived exertion of "light." Average RPE was not significantly different by job type ($p = 0.10$) or work condition ($p = 0.18$).

Maximal thermal discomfort was significantly higher in uncovered (2.9 ± 1.5) than covered (2.0 ± 1.0) workers ($p = 0.05$), while there were no significant differences by job type ($p = 0.12$). There were no differences in mean thermal discomfort by job type ($p = 0.06$), but uncovered workers (2.4 ± 1.2) had a higher mean thermal discomfort than covered workers (1.5 ± 0.59) ($p < 0.01$). A significant, positive relationship was found between maximal thermal discomfort and peak chest skin temperature ($r = 0.39$, $p = 0.03$).

Variables related to peak core temperature

A correlation matrix of the nine variables was created to better understand associations with peak Tcore (Figure 4). Correlation analyses revealed

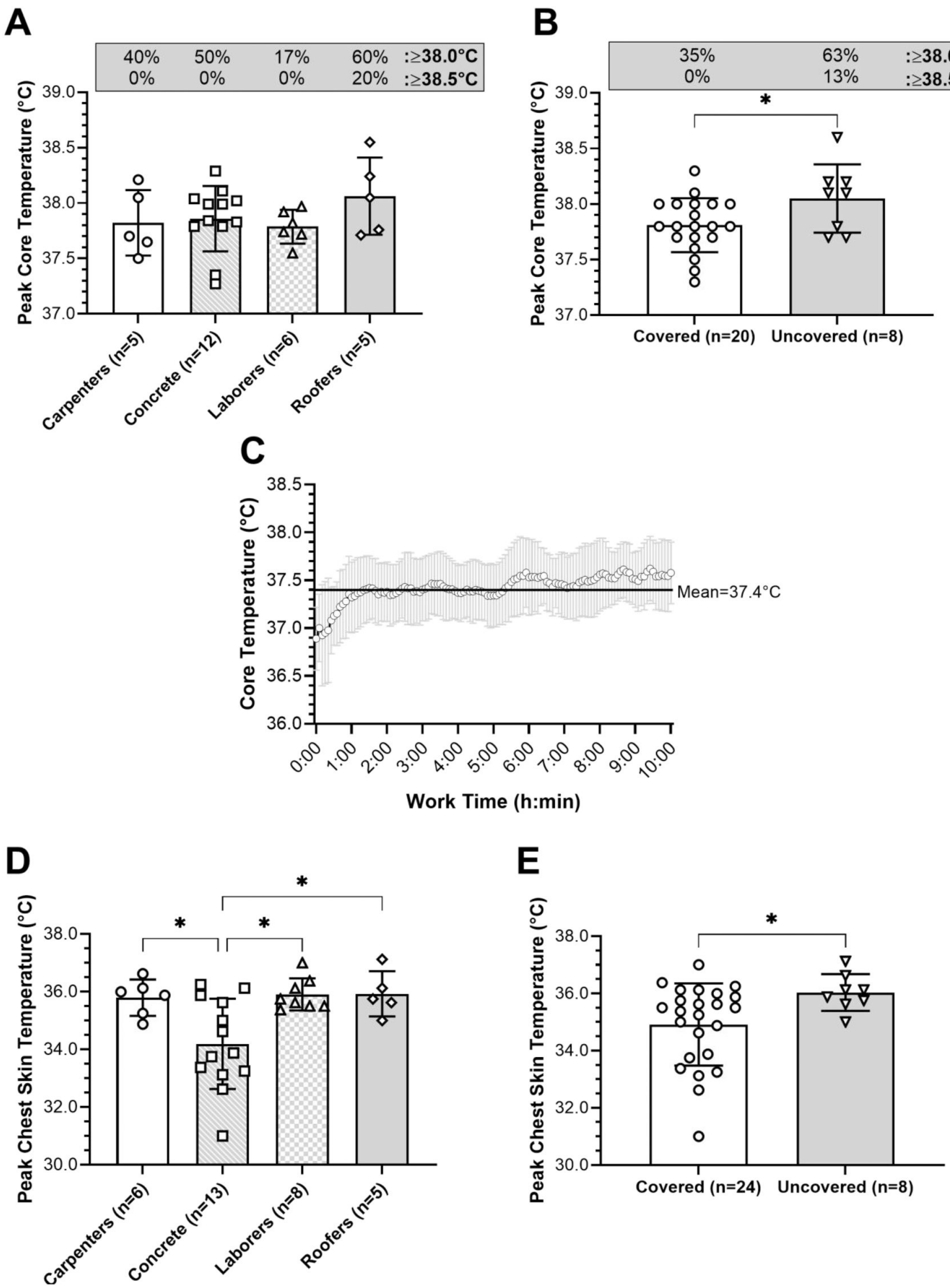

Figure 2. Core temperature and peak chest skin temperature values during a work shift in construction workers. Peak core temperature values reported as mean ± standard deviation and prevalence (percentage) of peak values being greater than 38.0 °C and 38.5 °C, respectively, categorized by job type (A) and work conditions (B). Core temperature of all workers throughout the workday is reported as mean ± standard deviation (C). Peak chest skin temperature is reported as mean ± standard deviation categorized by job type (D) and work conditions (E). A–C, $N = 28$; D, E, $N = 32$. * indicates significant difference between work groups ($p < 0.05$). Created with GraphPad prism.

several variables correlated with peak Tcore, including a positive correlation with mean thermal discomfort ($r = 0.43$, $p = 0.02$), post-shift USG ($r = 0.64$, $p < 0.01$), and peak metabolic rate ($r = 0.65$, $p < 0.01$). A weaker, positive but non-significant correlation was noted between peak heat index and peak Tcore ($r = 0.38$, $p = 0.08$). There were no significant relationships between peak Tcore and age

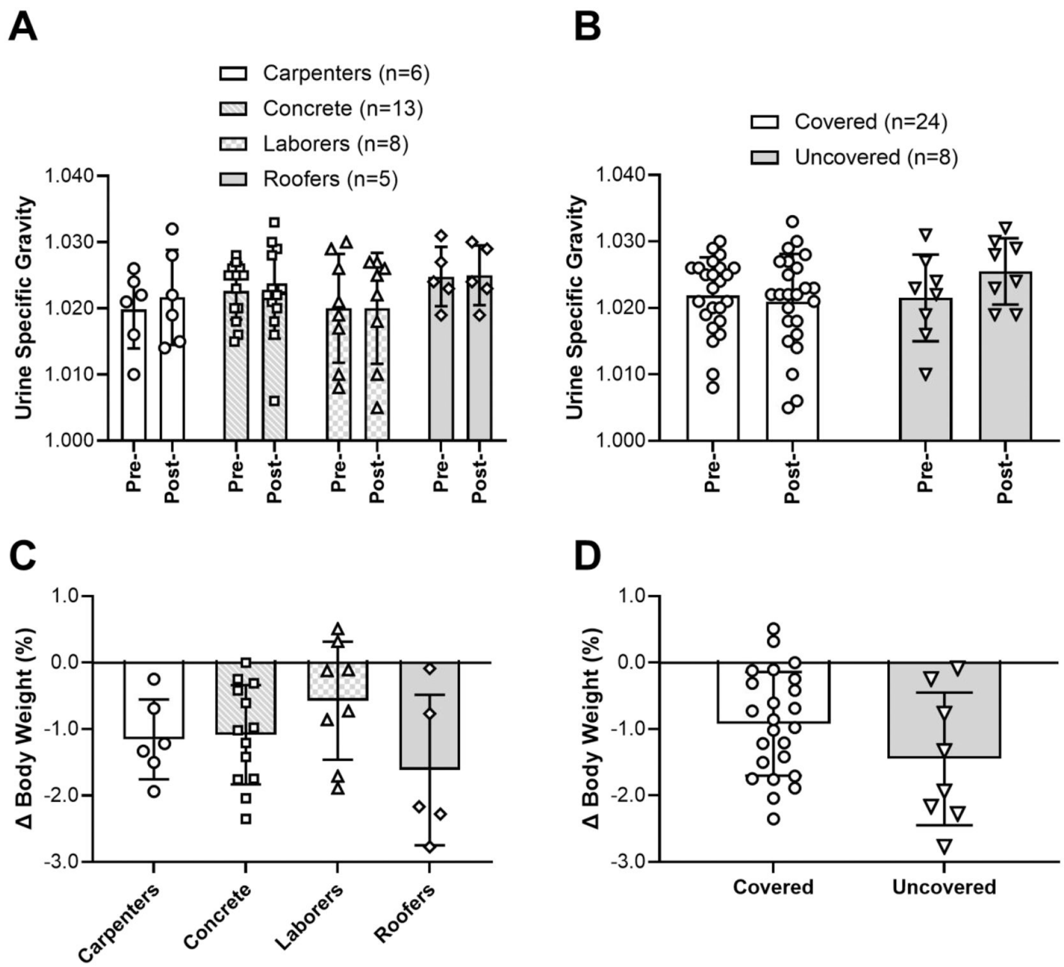

Figure 3. Hydration assessed via urine specific gravity categorized by job type (A) and work environment (B), and hydration assessed via percent change (Δ) in body weight categorized by job type (C) and work environment (D) ($N = 32$). No significant differences in urine specific gravity or change in body weight by job type or work environment ($p > 0.05$). Created with GraphPad prism.

($r = -0.21$, $p = 0.29$), BMI ($r = 0.20$, $p = 0.32$), change in body weight ($r = -0.32$, $p = 0.09$), pre-shift USG ($r = 0.27$, $p = 0.16$) or peak chest skin temperature ($r = 0.21$, $p = 0.29$).

Stepwise regression modeling revealed that post-shift USG and peak metabolic rate were significantly associated with peak Tcore ($r^2 = 0.55$, $p < 0.01$). The resultant regression was peak Tcore = 21.46 + 15.64 (post-shift USG) + 0.0006 (peak metabolic rate), as the intercept (CI = 8.27 to 34.64, $p < 0.01$), post-shift USG (CI = 2.61 to 28.68, $p = 0.02$), and peak metabolic rate (CI = 0.0002 to 0.0011, $p = 0.01$) were all significantly associated with peak Tcore.

Discussion

This study aimed to measure heat stress and heat strain in construction workers during work in the summer. The primary finding was that 43% of workers reached a peak Tcore of greater than 38.0 °C, surpassing ACGIH recommendations (ACGIH 2024), with 4% of workers exceeding 38.5 °C in low to moderate environmental heat stress. Additionally, 63% of workers arrived at the job site and began work in a dehydrated state (USG >1.020). Finally, in stepwise regression analysis, it was found that peak metabolic rate and post-shift USG were the most associated with peak Tcore in workers. To the authors' knowledge, this is the first study in the United States to report Tcore in construction workers during work in the summer.

Hyperthermia caused by high metabolic rate and/or environmental heat exposure is associated with an increased risk of heat illness (Leon and Bouchama 2015). In addition to the well-known health risks of environmental heat exposure, it is known that heat exposure affects productivity by reducing work output as heat stress increases. In agricultural workers,

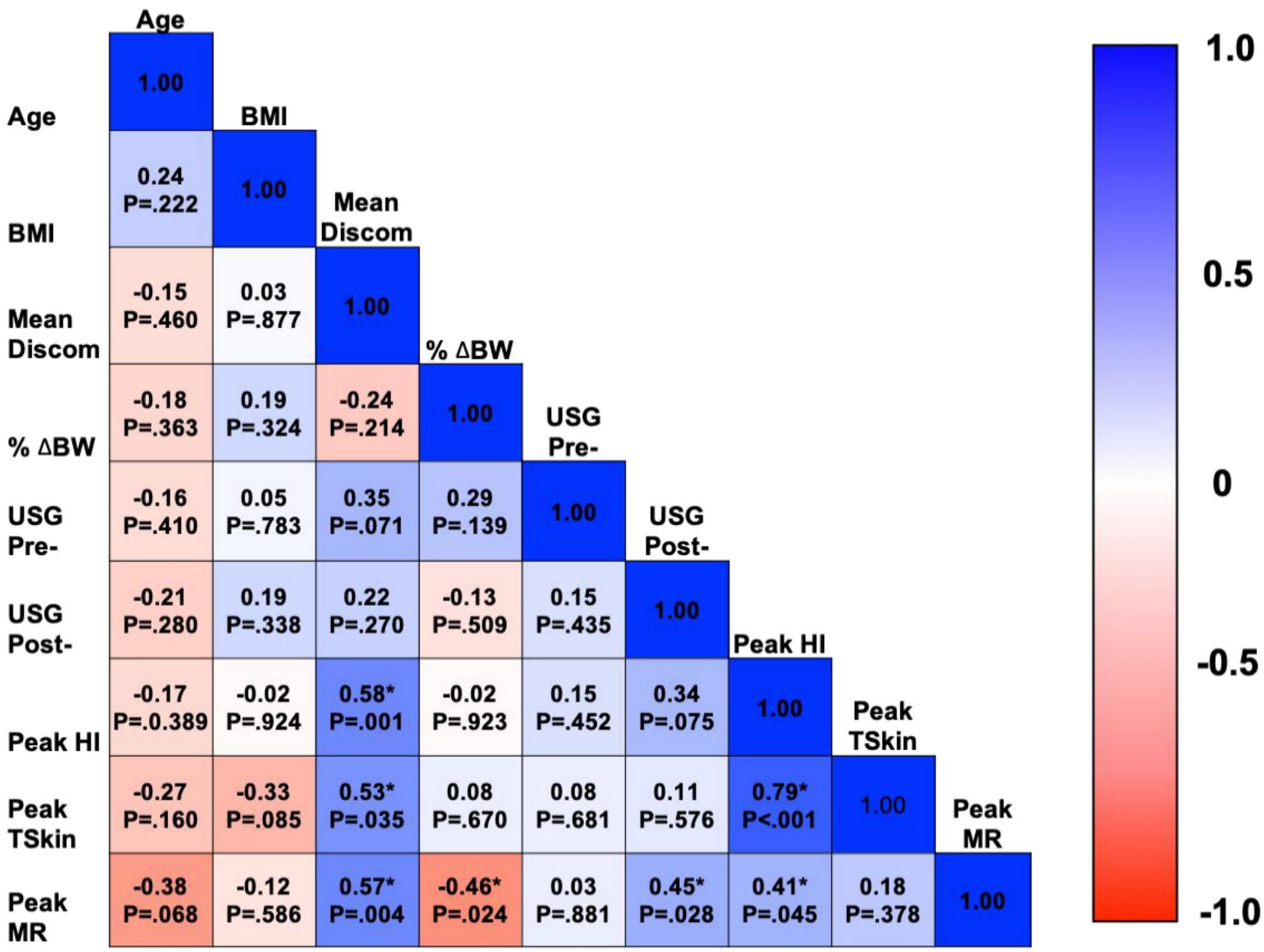

Figure 4. Correlation matrix of the strength of linear relationship (r) between the age, body mass index (BMI), mean thermal discomfort (discom), percent change in body weight (% ΔBW), pre-shift urine specific gravity (USG pre-), post-shift urine specific gravity (USG post-), peak heat index (HI), peak chest skin temperature (skin), and peak calculated metabolic rate (MR) during a work shift. The correlations are color-coded so that blue is a positive linear relationship and red is a negative linear relationship. Correlations made with peak MR $n = 25$, whereas $n = 28$ for all other variables. * indicates a significant correlation at $p < 0.05$.

Table 4. Rating of perceived exertion and thermal discomfort by job type in construction workers.

Variables	Carpenter ($n = 6$)	Concrete ($n = 13$)	Laborer ($n = 8$)	Roofer ($n = 5$)	Total ($N = 32$)
Max. RPE	16.5 ± 1.7	13.1 ± 2.9	11.9 ± 3.6	14.6 ± 3.3	13.7 ± 3.4
Mean RPE	13.8 ± 2.2	10.6 ± 2.7	10.3 ± 2.8	12.0 ± 2.6	11.3 ± 2.9
Max. Discomfort	2.0 ± 0.6	1.8 ± 1.0	2.1 ± 1.1	3.4 ± 1.5	2.2 ± 1.1
Mean Discomfort	1.7 ± 0.5	1.4 ± 0.7	1.5 ± 0.5	2.8 ± 1.3	2.2 ± 1.2

Note: No significant differences among job types ($p > 0.05$), Max. = maximal, RPE = rating of perceived exertion.

productivity reductions of approximately 5% per degree Celsius increase in WBGT above 26 °C have been reported (Sahu et al. 2013). The present study observed that 43% of workers reached a peak Tcore greater than 38.0 °C, with 4% exceeding 38.5 °C under moderate environmental heat load. The prevalence of hyperthermia reported here is slightly lower than that reported in previous research in occupational settings in the U.S. For instance, Mac et al. (2021) found that 49% of agricultural workers in Florida exceeded a Tcore of 38.0 °C, and 10% surpassed 38.5 °C. However, it is important to note that the heat index was much greater in their study, with an average HI of 32.3 °C compared to the average peak HI of 27.8 °C recorded by this study.

When analyzing the impact of job location on heat strain, this study demonstrated that workers had a higher Tcore in uncovered areas compared to those in covered work areas, potentially increasing their risk for heat-related illnesses (Flouris et al. 2018). These findings contrast with the work of Ioannou et al. (2021), who reported similar Tcore values for workers under direct sunlight and those with lower solar radiation levels. However, it is necessary to point out that their study matched overall WBGT and only compared differences in solar radiation. In contrast, this study covered workers who might have been exposed to lower environmental heat load associated with different metabolic rates.

Interestingly, it was observed that one roofer experienced a Tcore exceeding 38.5 °C, while three out of five roofers (60%) experienced a peak Tcore greater than 38.0 °C. Although roofers did not have significantly higher peak Tcore compared to other job types, they had a higher prevalence of surpassing the occupational exposure limit peak Tcore of 38.0 °C and 38.5 °C. These findings suggest a potential greater risk for heat-related illnesses among roofers, consistent with the findings of Dong et al. (2019). Indeed, Dong et al. demonstrated through survey data that roofers had a higher risk for heat-related death compared to helpers, brick masons, construction laborers, and heating, air conditioning, and refrigeration mechanics, but less than cement workers.

Approximately 75% of the energy used during physical work is lost as heat (Wendt et al. 2007). Consistent with this, an observed positive correlation was observed between peak metabolic rate and peak Tcore. The observed average estimated metabolic rate of 380 W was similar to the findings of Poulianiti et al. (2019), who estimated a metabolic rate of 345 W in construction workers. That said, the findings were notably higher than the metabolic rate of 151 W/m^2 reported by Li et al. (2019) in Chinese construction workers, which is equivalent to 272 W when assuming a standard BSA of 1.8 m^2. When looking at metabolic rate data by job type, Li et al. (2019) found that carpenters had an average metabolic rate of 159 W/m^2 (~286 W), while carpenters in this study had an average rate of 424 W. Similarly, the reported average rate of 510 W for laborers, whereas Li et al. reported 140 W/m^2 (~252 W) for this job type. Discordance in previous literature is likely due to variability in work effort depending on the construction project. Nevertheless, estimates of metabolic rate are generally consistent with the literature.

The relationship between peak metabolic rate and peak Tcore, even when accounting for post-shift USG, suggests that elevated Tcore is associated with workload. The data indicated that the heat strain observed in these moderate environmental heat loads was more heavily influenced by metabolic demands. However, there would likely be a greater contribution from environmental heat in hotter conditions. Also, this study may have been underpowered to observe a significant correlation between peak HI and peak Tcore ($p = 0.08$). To this end, roofers, who had the highest metabolic rate and exposure to the highest HI, exhibited a significantly greater prevalence of exceeding the Tcore threshold of 38.0 and 38.5 °C, respectively. The unique combination of constant movement, high metabolic workloads, prolonged exposure to both direct and reflected sunlight in roofers increases overall heat strain, elevating the risk of heat-related illness when compared to other construction workers (Breloff et al. 2019; Flouris et al. 2018; Wang et al. 2017). These findings align with research indicating that people working in direct sunlight are more likely to experience symptoms of heat strain, including dizziness and weakness (Ioannou et al. 2021).

Another major finding of this study was that the majority (63%) of workers arrived at work in a dehydrated state (USG > 1.020). The average pre-shift USG of 1.022 was only slightly higher than that found in a study on Japanese construction workers, where the average baseline USG was 1.019 (Ueno et al. 2018). An interesting finding was the strong correlation between post-shift USG and peak Tcore, even after accounting for changes in peak metabolic rate. Similar findings were reported by Lutz et al. (2014), who found a significant correlation between post-shift USG and peak Tcore while assessing heat strain in metal miners. Dehydration and elevated Tcore are intertwined, as dehydration throughout the work shift may lead to impaired sweating and associated heat loss that cools the body, resulting in further elevations in Tcore (Pearcy et al. 1956; Sawka et al. 1998). Simultaneously, individuals with a higher Tcore are likely to sweat more, leading to greater dehydration throughout the work shift (Périard et al. 2021; Sawka et al. 1998). Regardless, assessing hydration via USG throughout a work shift, rather than just at the beginning, may provide effective information to guide the use of safety measures to reduce the prevalence of hyperthermia and consequential heat illness. Although water was freely available in large quantities throughout all work areas at the job site, future interventions may focus on more frequent work breaks to allow workers adequate time for hydration throughout the workday.

In addition to assessing USG, the study also found that 5 of 32 workers lost more than 2.0% of their body weight throughout the workday. Previous research has shown that dehydration exceeding 2.0% bodyweight significantly decreases work capacity, increases markers of acute kidney injury, and may increase the risk of experiencing heat illness (Chapman et al. 2020; Institute of Medicine 2005).

Laboratory and field studies have demonstrated that dehydration is a risk factor for acute kidney injury and may contribute to the development of chronic kidney disease (Chapman et al. 2020; García-Trabanino et al. 2015; Nerbass et al. 2017). Regarding to risk of heat illness, three of the five workers who surpassed the 2.0% bodyweight loss threshold were roofers, who also had the highest metabolic rate and peak Tcore. Altogether, the job demands of roofers may put them at a much greater risk for heat illness, and additional efforts should be made to ensure safety in this population. Possible interventions may include active cooling strategies and increased rest breaks to reduce overall metabolic load in these workers. However, future work is required to determine the efficacy of such interventions.

The study's finding that chest skin temperature was significantly higher in uncovered than covered workers aligns with previous research showing that skin temperature increases due to increased solar radiation, even when overall WBGT is matched (Ioannou et al. 2021). Assessing skin temperature provides valuable insight during periods of heat stress, as skin temperature serves as a major feedback mechanism for the thermoregulatory system, inducing greater cutaneous vasodilation and ultimately a greater release of heat from the body (Romanovsky 2014). Skin temperature at the chest site was assessed, which has been assessed previously together with other measurements to classify heat strain risk (Buller et al. 2008). However, while increased skin temperature is associated with heat strain, workers in high-pressure job environments, such as construction, may not prioritize thermal discomfort due to production demands and workplace expectations.

Given that uncovered workers experienced significantly higher heat strain, effective cooling strategies may be necessary to reduce the risk of heat-related illnesses. However, limited research has been done on the implementation of cooling strategies for workers in the heat, including cooling gear, enhanced heat dissipation clothing, water dousing, ingestion of ice slushies, and electrolyte liquid hydration (Chicas et al. 2020). Research investigating strategies to maximize heat stress mitigation during work and post-work recovery behaviors as components of a comprehensive intervention strategy, along with attention on worker education, is also needed.

Limitations

As this was a pilot study, there are limitations due to the small sample size. For example, the relatively small sample size was likely insufficient to uncover significant differences in metabolic rate and Tcore among job types. Additionally, the small sample combined with collecting data for each individual on a single day, while the study spanned over separate days, means that there was inter- and intra-individual variation, as well as variations in the day-to-day job and environmental conditions. While individuals were incorporated into the mixed effects model as a random effect, there may still be an effect of the variability of the job demands. Thus, further research is needed to thoroughly quantify heat strain in construction workers across varying degrees of heat stress while accounting for rest and hydration. Another limitation of this study was that it was conducted during an atypically cooler week in July, with a peak dry bulb temperature of 31.4 °C, whereas the previous and following weeks reached temperatures of 35 °C or higher. Despite this, the study provides evidence that even under conditions of moderately hot environmental conditions, many construction workers experience significant heat strain.

Additionally, the study was limited in its ability to measure radiant heat in an uncovered environment due to a device malfunction preventing the use of globe temperatures. This limited the ability to quantify differences in radiant heat exposure for uncovered workers compared to covered workers. While the study did not find a significant difference in peak HI between covered and uncovered workers, the respective average peak HI values of 28.8 °C and 32.1 °C may be meaningfully different when assessing overall thermal stress. A larger sample size or a sample period greater than 3 days, combined with capturing radiant heat for the uncovered environment, would result in a significant difference in environmental thermal load. Finally, most workers started their work shift between 3:30 and 5:30 am, and this can reduce the applicability of the results presented in this study. While these early shifts protected workers from the hottest hours of the day, these measurements may not fully represent construction work that extends into the afternoon when environmental thermal loads peak.

Conclusions

In conclusion, 43% of construction workers exposed to low to moderate hot environmental conditions experienced significant heat strain during a typical work shift in the summer. This strain likely results from metabolic heat generated during physical labor, and likely the environment for workers engaged in construction work in covered and uncovered locations. Another major finding was that a majority of construction workers come to work in a dehydrated state, and that peak metabolic rate and post-shift USG were significantly associated with peak Tcore. Exploring factors associated with heat strain is feasible, and findings from this pilot study highlight the importance of future research on a larger scale. Employers should consider implementing more rigorous hydration protocols and rest breaks, especially for tasks performed in the summer months in uncovered areas.

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Data availability statement

The data that support the findings of this study are available from the corresponding author, JWS, upon reasonable request.

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