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*Original Article*

# Physiological and environmental assessment of heat strain risk among welders using the predicted heat strain model

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## ABSTRACT

**Introduction:** Welders are routinely exposed to high thermal loads, increasing the risk of heat stress. Environmental indices such as the Wet-Bulb Globe Temperature (WBGT) are commonly used for assessment but do not account for individual physiological responses. This study aimed to assess heat strain among welders using the Predicted Heat Strain (PHS) model defined by ISO 7933:2018 and to identify worker subgroups at higher risk.

**Methods:** An observational study was conducted in February 2025 among 41 male welders from the Kapal Niaga Division of PT PAL Indonesia, selected using total sampling. Environmental parameters were measured with a heat stress monitor, while metabolic rate was estimated through task observation and standardized values. Predicted water loss was calculated using the PHS model, and group differences were analyzed with independent samples t-tests.

**Results:** All participants experienced predicted water loss exceeding the 5% threshold recommended by ISO 7933:2018, ranging from 6.02% to 14.59%, indicating substantial heat strain risk. The average WBGT was 26.11 °C, surpassing the 25 °C limit for very high metabolic workloads. Welders with body weight below 65 kg had significantly higher proportional water loss (mean = 12.29%, SD = 1.62) compared to those with ≥65 kg (mean = 9.11%, SD = 1.51; $t = 6.50$, $p < 0.001$), suggesting that lower body mass may increase vulnerability to heat strain.

**Conclusion:** Welders face substantial heat strain risk, particularly those with lower body mass. Combining physiological modelling with environmental assessment offers a more complete evaluation of heat exposure risks. Preventive strategies should address both environmental and individual factors to enhance worker protection.

**Keywords:** Predicted heat strain, risk assessment, water loss, welders

## Introduction

Welding is a fundamental process in the shipbuilding industry, widely used to fabricate and assemble metal structures.[1] However, welding exposes workers to various occupational hazards, with excessive heat being a primary concern.[2] During welding operations, workers encounter extreme thermal conditions from open flames, infrared radiation, molten metal splashes, and contact with hot surfaces. To minimize the risks associated with heat exposure, welders are required to wear flame-resistant protective clothing made from high-density cotton fabrics.[3] While these garments provide necessary protection, they also reduce the body's ability to dissipate heat effectively, thereby increasing the risk of heat strain.

Heat stress has become an increasingly serious occupational health concern, especially for workers who must wear protective clothing in a high-temperature environment.[4] The inability to release body heat efficiently can lead to severe physiological consequences, including dehydration, cognitive impairment, and a higher likelihood of occupational injuries. Long-term exposure to excessive heat has also been associated with chronic health outcomes such as kidney disease and cardiovascular problems.[5] As climate change continues to raise global temperatures, the intensity and frequency of heat-related illnesses in the workplace are expected to rise.[6] In many tropical industrial settings, the actual heat burden remains poorly understood because indoor temperatures frequently exceed outdoor ambient conditions, leading to unmonitored physiological strain.[7] This situation becomes even more critical in tropical countries such as Indonesia, particularly in cities like Surabaya, which record some of the highest ambient temperatures and lowest humidity levels in the nation.[8] These climatic characteristics create an especially challenging environment for industrial workers exposed to heat.

In addition to environmental heat, working hours play a crucial role in determining the risk of heat stress. Most countries, including Indonesia, implement standard working hours from 8 am to 6 pm, a period that coincides with peak daytime heat.[9] For outdoor and industrial workers, such as welders in shipyards, this means prolonged exposure to thermal hazards during their shifts. When combined with protective clothing, environmental heat, and physical exertion, the risk of heat strain increases significantly.

Traditionally, occupational heat stress has been assessed using environmental indices such as the Wet-Bulb Globe Temperature (WBGT) index.[10,11] While useful, this approach has significant limitations because it does not account for individual physiological responses such as metabolic rate, core body temperature, and sweat rate, which are critical determinants of heat strain.[12] To address these limitations, ISO 7933:2018 introduces the Predicted Heat Strain (PHS) model, a more advanced framework that integrates environmental and physiological parameters to estimate the acceptability of exposure conditions.[13] This model enables more precise predictions and can inform preventive interventions in occupational settings.

Despite its advantages, the application of the PHS model in various industries remains limited. Several studies highlight barriers such as the complexity of data collection, the need for accurate physiological measurements, and challenges in adapting the model to local working conditions.[14,15] Computational tools such as the FAME Lab PHS Calculator have been developed to facilitate the implementation of the PHS model, enabling more accurate and accessible heat stress assessments.[13] However, research on the implementation of this model in Indonesia, particularly in industrial settings like shipyards, remains scarce. Existing studies have predominantly focused on environmental measurements without integrating workers' physiological responses, which limits the comprehensiveness of heat stress evaluation. To address this gap, the present study applies the ISO 7933:2018-based PHS model to welders at a shipbuilding company, integrating both environmental and physiological parameters to provide a more complete assessment of heat stress risk. By doing so, this study extends the context of previous research conducted in Indonesia by evaluating the PHS model in an industrial shipyard setting, providing insights that have not been previously addressed.

Given these considerations, this study aims to analyze occupational heat stress risks using the PHS model as defined in ISO 7933:2018 and to provide strategic recommendations for protecting workers from heat-related health issues. Specifically, the study will be conducted at PT PAL Indonesia, one of the country's largest and most prominent shipbuilding companies, located in Surabaya—a city with an especially high thermal burden.[16] By leveraging quantitative workplace data, this research will identify key risk factors, estimate acceptable exposure limits, and develop mitigation strategies that integrate both environmental and physiological dimensions of heat strain. Furthermore, the findings are expected to fill a critical knowledge gap in the practical application of the PHS model in Indonesia and contribute to the development of more robust occupational heat stress management frameworks tailored to tropical industrial environments.

## Methods

This observational study was conducted among welders in the Kapal Niaga Division of PT PAL Indonesia on 20 February 2025. Ethical approval was obtained from Komisi Etik Penelitian Kesehatan STIKES Guna Bangsa Yogyakarta (approval number 022/KEPK/VI/2025), and written informed consent was secured from all participants prior to data collection. A total of 41 male welders participated in the study. Total sampling was employed, meaning all welders in the Kapal Niaga Division were included, and no specific inclusion or exclusion criteria were applied apart from being a welder. No experimental intervention was introduced to maintain the authenticity of the working environment and participants' responses.

Participant data were collected using a structured questionnaire that included questions on age, body weight, height, duration of employment, and working posture. All participants wore identical personal protective equipment (PPE), specifically coverall-type garments made of cotton with aluminum-painted reflective surfaces, ensuring consistency in clothing-related variables.

According to the National Institute for Occupational Safety and Health (NIOSH),[17] full heat acclimatization is assumed in workers who have been gradually exposed to hot environments for at least 7–14 consecutive days. In this study, acclimatization status was determined based on the duration of employment obtained from the structured questionnaire. All participants met this criterion, having worked in the hot welding environment for a period exceeding this threshold. Environmental parameters, namely dry-bulb, wet-bulb and globe temperature, relative humidity, and air velocity, were measured using the TSI QUESTemp° 44 Heat Stress Monitor. The instrument was calibrated prior to data collection according to the manufacturer's specifications to ensure measurement accuracy. Measurements were taken three times during an 8-hour work shift: at the beginning (07:00–08:00), middle (11:00–12:00), and end of the shift (15:00–16:00). The middle shift measurement was selected to capture the period of peak heat exposure. Measurement points were located directly at the workers' operating areas to ensure accurate representation of environmental conditions.[18]

The Wet-Bulb Globe Temperature (WBGT) Index was used to assess heat stress risk. The WBGT was calculated in accordance with ISO 7243:2017 using the following equation:[19]

$$WBGT = 0.7t_{nw} + 0.2t_g + 0.1t_a$$

where $t_{nw}$ is natural wet-bulb temperature, $t_g$ is black globe temperature and $t_a$ is air temperature. The WBGT for each participant was calculated based on the average of the three measurements taken during the work shift.

Thermal stress among workers was assessed using the Predicted Heat Strain (PHS) model, as outlined in ISO 7933:2018. The PHS model estimates water loss due to heat exposure using computational analysis via the FAME Lab PHS Calculator. The input variables included worker characteristics, environmental parameters, metabolic rate, mechanical efficiency, movement speed during work, and thermal and evaporative properties of clothing. Figure 1 illustrates the input variables and interface of the calculator. Movement speed during work was uniformly set at 4.99 km/h based on a meta-analysis by Bohannon & Williams Andrews (2011),[20] which represents the average walking speed during moderate-intensity manual labour.

Metabolic rate (M) was calculated using the following formula:

$$M\ (in\ W/m^2) = \frac{M\ (in\ Watt)}{ADu}$$

where $M\ (in\ Watt)$ is the maximum work capacity in watts and $ADu$ is the individual body surface area, calculated using the DuBois and DuBois (1916) formula.

Maximum work capacity $M\ (in\ Watt)$ was estimated by the following equation:

$$M\ (in\ Watt) = (19.45 - 0.133 \times Age)\ Wbl$$

where $Wbl$ represents lean body mass, which was calculated using the following formula:

$$Wbl = \frac{1.08 - Wb}{(80 \times Hb^2)} \times Wb$$

where $Wb$ is body mass (kilograms) and $Hb$ is body height (meters).

Mechanical efficiency ($\eta$) defined as the fraction of metabolic energy converted to external work, was estimated using the Fiala equation:

$$\eta = 0.2\ tanh\left(0.39\left(\frac{act}{58.15}\right) - 0.60\right)$$

where $act$ represents the standardized level of physical activity in $W/m^2$.

Descriptive statistics were used to summarize the participants' characteristics, environmental parameters, and physiological responses, including predicted water loss. Differences in water loss percentage between body weight groups (<65 kg vs. ⩾65 kg) were analyzed using an independent sample t-test after confirming normality through the Shapiro-Wilk test. The cut-off value of 65 kg was selected based on the median body weight of the study population. All statistical analyses were conducted using Python programming language in the Google Colaboratory environment. A p-value of less than 0.05 was considered statistically significant.

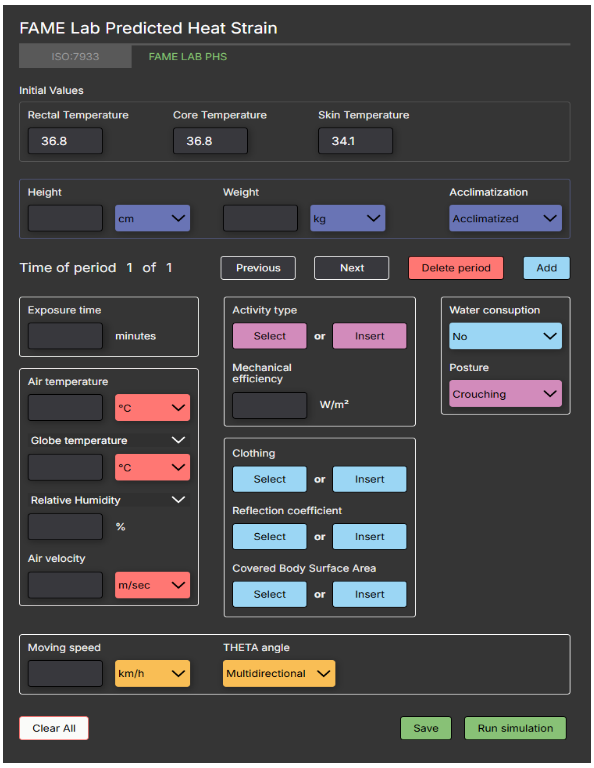


**Figure 1.** Snapshot of the FAME Lab PHS Calculator

## Results

A total of 41 male welders participated in this study, aged 21-47 years (SD = 7.32). Their average work experience was 8.80 years (SD = 6.84), indicating that all participants were fully acclimatized to heat according to NIOSH criteria. Key demographic and environmental characteristics, including height, weight, work duration, and thermal exposure during welding tasks, are summarized in Table 1. Most workers (78%) performed tasks in a standing posture, while the remaining participants worked in sitting or crouching positions (Figure 2).

Environmental measurements, including dry-bulb temperature, wet-bulb temperature, globe temperature, relative humidity, and air velocity, were taken three times during each work shift—at the beginning, middle, and end—at each measurement location. The reported values (Table 1) represent the averages of these three measurements to reflect the overall thermal exposure throughout the shift.

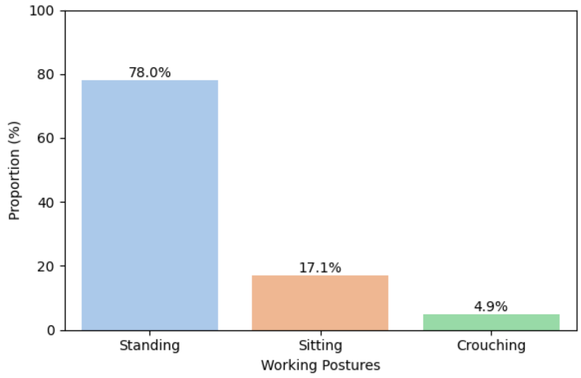


**Figure 2.** Distribution of work postures among participants during welding tasks.

Environmental conditions indicated relatively stable thermal patterns throughout the observation period, as demonstrated by the low standard deviations across all measured parameters. The average wet-bulb temperature was 23.45°C (SD = 0.17), the dry-bulb temperature was 32.25°C (SD = 0.17), and the globe temperature was 32.35°C (SD = 0.05). The mean relative humidity recorded was 44.87% (SD = 0.30), and the average air velocity was 0.66 m/s (SD = 0.06).

**Table 1:** Participants' demographic characteristics and environmental measurements during welding tasks (n = 41)

| Variables | Min | Max | Mean | Standard Deviation |
|---|---|---|---|---|
| Age (year) | 21 | 47 | 33.27 | 7.32 |
| Height (cm) | 157 | 177 | 165.95 | 4.88 |
| Weight (kg) | 48 | 96 | 64.95 | 11.55 |
| Work duration (year)* | 0.25 | 27 | 8.80 | 6.84 |
| Metabolic rate (watt) | 550.90 | 721.46 | 640.71 | 46.46 |
| Wet-bulb temperature (℃) | 23.2 | s23.6 | 23.45 | 0.17 |
| Dry-bulb temperature (℃) | 32 | 32.4 | 32.25 | 0.17 |
| Globe temperature (℃) | 32.3 | 32.4 | 32.35 | 0.05 |
| Relative humidity (%) | 44.6 | 45.3 | 44.87 | 0.30 |
| Air velocity (m/sec) | 0.54 | 0.72 | 0.66 | 0.06 |
| WGBT (℃) | 25.9 | 26.24 | 26.11 | 0.14 |
| Predicted Water loss (gram) | 4944.8 | 7663.5 | 6700.15 | 625.22 |
| Age (year) | 21 | 47 | 33.27 | 7.32 |
| Height (cm) | 157 | 177 | 165.95 | 4.88 |
| Weight (kg) | 48 | 96 | 64.95 | 11.55 |
| Work duration (year)* | 0.25 | 27 | 8.80 | 6.84 |

Note. *Acclimatization status was inferred based on participants' work duration following NIOSH criteria.

The wet-bulb globe temperature (WBGT), a widely used index for assessing heat stress, reflects the thermal environment to which an individual is exposed. Accurate interpretation of WBGT values requires consideration of the individual's metabolic rate. The average metabolic rate among participants was 640.71 W (SD = 46.46), with values ranging from 550.90 W to 721.46 W. Based on ISO 7243:2017, this level of energy expenditure corresponds to Class 4, which is categorized as a very high metabolic rate. For workers in this category, the recommended

WBGT reference limit is 25°C. However, the measured average WBGT in this study was 26.11°C (SD = 0.14), exceeding the recommended threshold. This suggests that participants were working under environmental conditions that posed a significant risk of heat stress.

Thermal stress was evaluated using the Predicted Heat Strain (PHS) model, as defined in ISO 7933:2018, which determines physiological strain based on predicted water loss and rise in core temperature. The results showed notable variability in the predicted water loss, ranging from 4,944.8 g to 7,663.5 g. These values corresponded to between 6.02% and 14.59% of each participant's body weight. All 41 participants experienced water loss exceeding 5% of their body weight, which is the maximum allowable limit defined in ISO 7933:2018 for maintaining thermal balance and preventing excessive dehydration. To facilitate understanding of how each participant's predicted water loss compares to this limit, Figure 3 illustrates a comparison between actual water loss and the maximum allowable limit (5% of body weight). This visualization highlights the extent to which predicted values exceed the acceptable level across the group.

Notably, participants with body weight below 65 kg exhibited a higher average water loss of 12.29% (SD = 1.62), compared to 9.11% (SD = 1.51) among those weighing 65 kg or more. This difference was statistically significant ($t = 6.50$, $p < 0.001$), indicating a greater physiological burden in the lower-weight group. Exceeding this threshold may impair thermoregulation, reduce physical and cognitive performance, and increase the risk of heat-related illnesses. Detailed individual data are presented in the Appendix.

These findings underscore the need for further interpretation regarding their implications for worker safety, particularly in relation to hydration, body composition, and heat exposure. A detailed discussion of these aspects is presented in the following section.

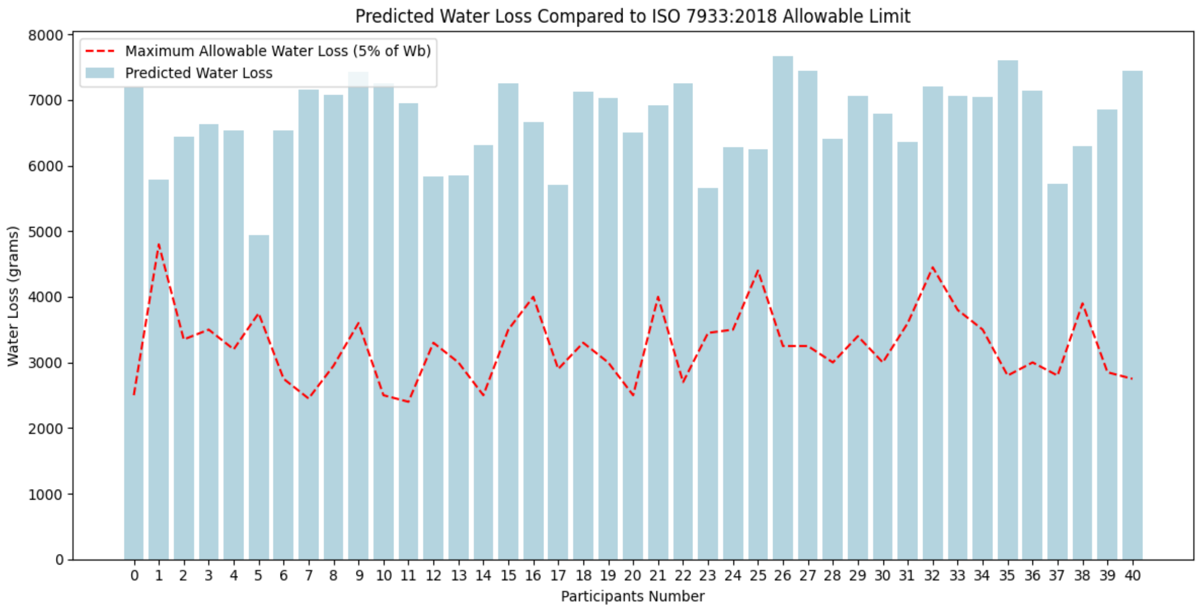


**Figure 3.** Comparison between predicted water loss and the maximum allowable limit (5% of body weight) for each participant.

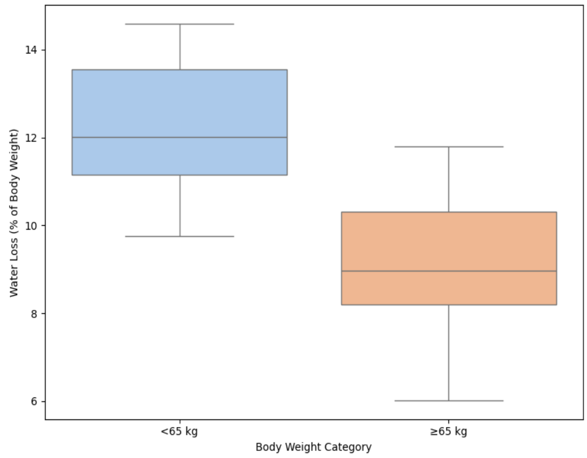


**Figure 4.** Comparison of water loss (% of body weight) between body weight category

## Discussion

The present study aimed to evaluate heat stress among welders by considering both environmental conditions and individual physiological responses. To better understand the physiological demands experienced by the participants, we examined their estimated metabolic rate. The average metabolic rate was 640.71 W, which, according to ISO 7243:2017, falls under Class 4, or "very high metabolic rate." For this category, the recommended WBGT reference limit is 25 °C. However, the measured average WBGT in the work environment was 26.11 °C, thereby exceeding the threshold defined by the standard. This discrepancy indicates that workers were exposed to environmental conditions that surpassed acceptable limits for their level of physical exertion, highlighting a substantial risk of heat stress even before accounting for individual physiological responses. These findings are further supported by Kim & Lee (2020),[21] who identified welding as one of the occupation types associated with high metabolic workloads (400–500 W) and elevated risk of heat exposure, based on national work conditions and climate data in Korea. Furthermore, research in industrial settings indicates that such thermal exposure imposes a significant cardiac burden and can lead to inadequate heart rate recovery among workers.[22]

The physiological risk became more evident when analyzed using the PHS model. All participants were predicted to experience water loss exceeding 5% of their body weight, with values ranging from 6.02% to 14.59%. This surpasses the maximum allowable limit recommended by ISO 7933:2018 for maintaining thermal equilibrium and preventing dehydration-related complications. Research has shown that water loss above 2% of body mass is associated with measurable declines in both physical and cognitive performance. For example, Young et al. (2019) found that moderate dehydration (2–5% body mass loss) can impair memory, focused attention, and cardiovascular stability.[23] Similarly, Wittbrodt & Millard-Stafford (2018) reported in their meta-analysis that cognitive domains such as executive function, attention, and motor coordination are particularly vulnerable to degradation as dehydration severity increases.[24] These findings suggest that the level of water loss predicted in this study may have serious implications for workers' health, cognitive function, and overall safety on the job.

Further analysis revealed a significant difference in proportional water loss based on body weight. Participants with body weight below 65 kg experienced higher water loss as a percentage of their body mass compared to those weighing 65 kg or more. This difference was statistically significant ($t = 6.50$, p value = 0.00), indicating a greater physiological burden among lighter individuals under the same environmental and task conditions. Prior studies have shown that individuals with lower body mass are more vulnerable to heat stress due to their smaller heat storage capacity and reduced ability to dissipate heat efficiently. Foster et al. (2020) identified low total body mass—particularly below 50 kg—as a major risk factor for thermal strain, noting a negative correlation between body mass and increases in core temperature during hot work.[25] Similarly, Ioannou et al. (2023) found that agricultural workers with smaller body sizes had higher heat-health risk profiles, emphasizing the role of body surface area in thermoregulation.[26] These findings support the current study's results and highlight the importance of considering body composition when evaluating individual susceptibility to occupational heat stress.

While these findings provide valuable insights into the role of body mass in heat stress susceptibility, several limitations should be considered when interpreting the results. First, movement speed during work was not measured directly but estimated based on a meta-analysis, which may not fully reflect actual work pace. Second, environmental parameters were recorded at specific time points rather than continuously, which may have missed short-term variations in heat exposure. Third, the sample consisted only of male welders from a single industrial site, limiting the generalizability of the findings.

Building upon these limitations, several avenues for future research can be identified. First, direct measurement of workers' movement speed using wearable sensors or video-based motion analysis would provide more precise data on physical workload compared to estimations from secondary sources. Second, continuous monitoring of environmental parameters with real-time logging devices is recommended to capture fluctuations in heat exposure that may occur throughout the work shift. Third, expanding the sample to include female workers, different job types, and multiple industrial settings would enhance the generalizability of the findings.

## Conclusion

This study assessed occupational heat stress among welders by integrating environmental measurements with physiological modeling using the Predicted Heat Strain (PHS) framework. The results demonstrated that all participants experienced water loss exceeding the 5% safety threshold specified in ISO 7933:2018, indicating a considerable risk of thermal strain. Measured WBGT values also exceeded the recommended limit for workers with very high metabolic rates, further compounding the heat exposure burden. Notably, participants with lower body weight experienced significantly greater proportional water loss, suggesting increased physiological vulnerability. These findings highlight the need for heat stress prevention strategies that account not only for environmental conditions but also for individual characteristics such as body mass. Implementing targeted control measures and regular physiological monitoring may enhance worker protection in hot occupational environments.

Further analysis revealed a significant difference in proportional water loss based on body weight. Participants with body weight below 65 kg experienced higher water loss as a percentage of their body mass compared to those weighing 65 kg or more. This difference was statistically significant ($t = 6.50$, p-value = 0.00), indicating a greater physiological burden.

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## Appendix

Participant-level data on WBGT, body mass, and water loss with reference to the 5% allowable limit.

| No. Participants | WGBT (℃) | Body Mass ($Wb$) (kilogram) | Predicted Water Loss (gram)* | Maximum Allowable Water Loss (5% of $Wb$) (gram) | Water Loss (% of $Wb$) (%)** |
|---|---|---|---|---|---|
| 0 | 26.24 | 50 | 7190.6 | 2500 | 14.38 |
| 1 | 26.24 | 96 | 5783.4 | 4800 | 6.02 |
| 2 | 26.24 | 67 | 6440.9 | 3350 | 9.61 |
| 3 | 26.24 | 70 | 6632 | 3500 | 9.47 |
| 4 | 26.24 | 64 | 6529.1 | 3200 | 10.20 |
| 5 | 26.24 | 75 | 4944.8 | 3750 | 6.59 |
| 6 | 26.24 | 55 | 6536.9 | 2750 | 11.89 |
| 7 | 26.24 | 49 | 7151 | 2450 | 14.59 |
| 8 | 26.24 | 59 | 7084.1 | 2950 | 12.01 |
| 9 | 26.24 | 72 | 7426.2 | 3600 | 10.31 |
| 10 | 26.24 | 50 | 7257.8 | 2500 | 14.52 |
| 11 | 25.92 | 48 | 6950.4 | 2400 | 14.48 |
| 12 | 25.92 | 66 | 5827.3 | 3300 | 8.83 |
| 13 | 26.04 | 60 | 5857.7 | 3000 | 9.76 |
| 14 | 26.04 | 50 | 6312.1 | 2500 | 12.62 |
| 15 | 26.04 | 70 | 7260.9 | 3500 | 10.37 |
| 16 | 26.04 | 80 | 6659.9 | 4000 | 8.32 |
| 17 | 26.04 | 58 | 5713.7 | 2900 | 9.85 |
| 18 | 26.04 | 66 | 7122.4 | 3300 | 10.79 |
| 19 | 26.04 | 60 | 7037.8 | 3000 | 11.73 |
| 20 | 26.04 | 50 | 6510.6 | 2500 | 13.02 |
| 21 | 26.04 | 80 | 6925.8 | 4000 | 8.66 |
| 22 | 26.04 | 54 | 7247.8 | 2700 | 13.42 |
| 23 | 25.92 | 69 | 5660.7 | 3450 | 8.20 |
| 24 | 25.92 | 70 | 6279 | 3500 | 8.97 |
| 25 | 25.92 | 88 | 6252.3 | 4400 | 7.10 |
| 26 | 25.92 | 65 | 7663.5 | 3250 | 11.79 |
| 27 | 25.92 | 65 | 7453.1 | 3250 | 11.47 |
| 28 | 25.92 | 60 | 6415.3 | 3000 | 10.69 |
| 29 | 25.92 | 68 | 7056.5 | 3400 | 10.38 |
| 30 | 26.24 | 60 | 6787.3 | 3000 | 11.31 |
| 31 | 26.24 | 72 | 6354.7 | 3600 | 8.83 |
| 32 | 26.24 | 89 | 7208.2 | 4450 | 8.10 |
| 33 | 26.24 | 76 | 7065.2 | 3800 | 9.30 |
| 34 | 26.24 | 70 | 7043.5 | 3500 | 10.06 |
| 35 | 26.24 | 56 | 7605.4 | 2800 | 13.58 |
| 36 | 26.24 | 60 | 7144.5 | 3000 | 11.91 |
| 37 | 25.92 | 56 | 5723.1 | 2800 | 10.22 |
| 38 | 26.24 | 78 | 6294.6 | 3900 | 8.07 |
| 39 | 26.24 | 57 | 6856.9 | 2850 | 12.03 |
| 40 | 26.24 | 55 | 7439.1 | 2750 | 13.53 |

Notes:

*Predicted Water Loss (gram) refers to the estimated amount of water loss for each participant, calculated using the Predicted Heat Strain (PHS) model.

** Water Loss (% of Wb) (%) represents the percentage of water loss based on each participant's body weight