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Physiological strain and postural stability impairment during occupational heat stress: a controlled chamber study across WBGT levels

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Research Article

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Abstract

Most occupational heat stress research has treated physiological strain and balance impairment in isolation, with limited studies measuring core temperature, cardiovascular responses, hydration status, and postural stability for construction workloads. The present study aims to determine how combined heat exposure and physical workload influence workers' physiological responses and balance ability. Ten healthy males participated in an experiment comparing physiological responses and deterioration of balance ability according to workload and heat exposure. The test protocol consisted of a 1-h workload test (walking at 5.5 km/h with 12% grade), 1-h recovery time (sitting), and three sets of body balance tests (body sway, functional reach test, and 2-step test). The test chamber was maintained at four different conditions (WBGT 22℃: 23℃, 70% RH, and 27℃, 40% RH; WBGT 29℃: 30℃, 70% RH, and 36℃, 40% RH). Heart rate and rectal temperature were monitored during the test. Physical workload and heat exposure impaired physiological responses and balance ability. Additionally, rectal temperature and body weight loss were significantly elevated in conditions with a WBGT of 29°C, confirming a heightened physiological strain. The body sway parameters showed a similar tendency, although no significant differences in functional reach and the 2-step test were observed. These findings emphasize the critical need for proactive heat stress management in industrial environments, particularly given increasing extreme thermal exposures due to climate change.

Introduction

With global surface temperatures rising by approximately 1.1°C since the late nineteenth century (IPCC, 2023), heatwave frequency, intensity, and duration have increased globally. Extreme heat events disproportionately impact outdoor workers, as prolonged exposure to high ambient temperatures and solar radiation can compromise the body's thermoregulatory capacity. Without adequate cooling strategies, outdoor workers face elevated risks of heat-related illnesses, diminished work capacity, and elevated accident rates. According to previous studies, global warming could raise the heat index and reduce worker performance by 4–10% in Southeast Asia (Amnuaylojaroen et al., 2022). De Sario et al. (2023) found that extreme heat reduces labor productivity by roughly 10% on average and that physically demanding sectors like agriculture and construction are expected to be the hardest affected. Thus, heat stress is becoming a substantial public health crisis for outdoor and industrial workers.

Workers in regions prone to high summer temperatures and humidity bear a particularly heavy burden. In humid summer climates (e.g. tropical Asia or Japan, and South Korea), high temperature and humidity sharply increase heat illness. Japan has areas prone to high temperatures and relative humidity during the summer season, which increases the incidence of heat stroke among outdoor workers. Official records from the Ministry of Health, Labour and Welfare in Japan (MHLW) indicate an average of 19.8 heat-related occupational deaths annually between 1998 and 2012 (n = 297) and 86 deaths from 2010 to 2012 (MHLW, 2014), and recent MHLW data (2025) confirm that this critical trend persists, with 1,257 occupational heatstroke casualties reported in 2024. Moreover, 32% of those incidents were reported in construction sites, the working in the construction sector remains one of the most vulnerable sectors to

extreme thermal environments. Construction workers account for a large share of new heatstroke incidents in Japan as summers grow hotter (Reuters, 2025). In the U.S., construction workers (6% of the workforce) accounted for 36% (n = 285) of all heat-related work fatalities from 1992 to 2016 (Dong et al., 2019). Globally, the International Labour Organization estimates that, by 2030, over 2 percent of total working hours will be lost due to heat stress, with construction workers disproportionately affected (International Labour Organization, 2019). More broadly, over 2.4 billion workers encounter extreme heat exposure annually, resulting in approximately 19,000 heat-related fatalities and 22.8 million work-related injuries (Building and Wood Workers' International, 2025).

Heat stress imposes physiological strain when environmental and metabolic heat gain exceeds heat dissipation mechanisms. Core temperature rises, heart rate (HR) escalates, sweat rates increase, and significant body mass loss can occur within a single shift (Ioannou et al., 2022). Early symptoms such as nausea, dizziness, and headaches indicate impaired thermoregulation and cognitive function, which can undermine postural control and dexterity. Outdoor workers such as construction workers are up to 13 times more likely to die from heatstroke than workers in other industries (Warburton, 2025).

Specht et al. (2025) found that 43% of U.S. construction workers exceeded a core temperature of 38.0°C during summer shifts with significant dehydration and elevated metabolic strain, despite only moderate heat indexes (Specht et al., 2025). Likewise, Lucas et al. (2023) reported that at about 58–59% of maximal HR, sugarcane harvesters reached estimated core temperatures near 38°C (Lucas et al., 2023). These findings suggest that even moderate environmental heat combined with heavy physical workload imposes substantial physiological strain on construction workers (Venugopal et al., 2025). A recent systematic review by Habibi et al. (2024) underscored limited heat stress resilience among outdoor workers in tropical and subtropical climates. Despite widespread adoption of the high wet-bulb globe temperature (WBGT) index for occupational heat stress assessment, its failure to account for individual factors, such as acclimatization, clothing insulation, and work intensity, may underestimate physiological strain on construction workers (Ioannou et al., 2022).

Heat stress diminishes work capacity via impaired postural control. Even mild hyperthermia degrades the integration of sensory inputs necessary for balance, leading to increased sway, reduced functional reach, and slower reaction times (Ioannou et al., 2022). Construction tasks, particularly those involving work at height and tool operation, necessitate a high degree of balance ability. Diminished balance directly elevates the risk of slips, trips, and falls on construction sites or fire scenes due to significantly impaired postural balance, which is revealed by increasing sway speed and area due to hyperthermia and muscular fatigue (Rossi et al., 2024; Aljaroudi et al., 2023). Thus, heat stress can increase the risk of potentially fatal accidents and injuries, such as falls from height (Tan et al., 2025).

Despite recognizing these risks, most occupational heat stress research has treated physiological strain and balance impairment in isolation, with limited studies measuring core temperature, cardiovascular responses, hydration status, and postural stability for construction workloads. This study, therefore, aims to determine how the combination of heat exposure and physical workload influences workers'

physiological responses and balance ability. Specifically, the author hypothesized that (H1) higher WBGT (29°C vs. 22°C) combined with physical workload (walking at 5.5 km/h for 60 min) will significantly amplify physiological strain, as reflected by elevated rectal temperature (Tre), HR, and Physiological Strain Index (PSI), and increased dehydration (body weight loss); and that (H2) this elevated physiological strain will significantly impair static postural ability compared with milder thermal conditions. By investigating these hypotheses, this study aims to clarify how varying WBGT levels, combined with a physical workload, affect physiological strain and static postural balance in healthy adult males under controlled laboratory conditions, thereby providing insights into how heat stress compromises safety among outdoor industrial workers.

Methods

Participants

While the proportion of female workers on construction sites has been gradually increasing, in Asian countries the industry remains predominantly male. For example, recent data from Statistics Korea indicates that women comprise only about 10.4% of the construction workforce (Lee, 2022). In other Asian countries, such as Indonesia, female participation is reported to be less than 3% (Hansen et al., 2020). Therefore, male participants were recruited exclusively for this study to reflect the primary demographics of the construction sites. Ten healthy males participated in an experiment comparing physiological responses and deterioration of balance ability in response to workload and heat exposure. The anthropometric characteristics of these ten healthy participants are expressed as mean ± standard deviation (SD): age 31.9 ± 7.9 year, weight 64.6 ± 6.7 kg, and height 171 ± 4.5 cm. Before participating, participants were informed about experimental procedures and provided verbal and written consent. All of the experimental procedures were approved by the institutional review board of the National Institute of Occupational Safety and Health, Japan (H2616). This study was conducted in accordance with the Declaration of Helsinki. All participants were fully informed about the study procedures and provided written informed consent prior to participation.

Experimental design and protocol

For the temperature and humidity setting of each condition, the temperature and RH corresponding to WBGT 22 ºC [Caution] and WBGT 29 ºC [Severe Warning] were set by referring to the relationship table between the WBGT value, temperature, and RH provided by the Japanese Society of Biometeorology (Watanabe et al., 2023). According to the unpublished data of the Japanese National Institute of Occupational Safety and Health Japan, heat stress among Japanese construction workers frequently occurs at temperatures and RH in the range of WBGT 29ºC. The experiment was conducted in a controlled environmental chamber maintained at four distinct temperature and RH combinations (W22-LT: 23ºC and 70% RH; W22-HT: 27ºC and 40% RH; W29-LT: 30ºC and 70% RH; W29-HT: 36ºC and 40% RH).

Upon arrival at the laboratory, participants consumed 180 mL of water and rested briefly. Fluid intake was not permitted during whole experimental period. After removing their personal clothing, body weight was measured. Body weight was measured using a calibrated digital scale immediately before and after the experiment. Following the measurement, physiological monitoring sensors were attached, and the participants changed into experimental clothing consisting of underwear, a T-shirt, a work suit, a helmet, gloves, and work shoes. The work suit, commonly used at Japanese construction sites, consisted of a long-sleeved jacket and pants and was made of 98% polyester and 2% polyurethane (Fig. 1).

The overall experimental protocol is illustrated in Fig. 2. The test protocol consisted of 20min of rest time for adaptation to the test chamber environment, 1-hr workload test (two sets of 25 min walking with a 10 min rest time in between, W1 and W2), followed by a 1-hr recovery time (including two sets of 25 min sitting, R1 and R2). The physical workload of walking exercise was below that; a speed of 5.5 $km \cdot h^{-1}$ and 12% grade were selected to represent a high metabolic workload based on the metabolic rate estimation procedures described in ISO 8996:2021. During the present test, every participant was tested for body balance performance four times: before and after the workload test (W1 and W2), during recovery, and at the end of recovery (R1 and R2). Additionally, subjective evaluations were reported at the end of every experimental period: rest, two sets of walking, and two sets of recovery.

Measurements

Physiological responses

Physiological responses were recorded during the experiment. Tre and skin temperature (Tsk) were measured and recorded every minute by thermistor sensors and a Gram LT-8 series data logger (Nikiso-Therm Co., Tokyo, Japan). Tsk was measured at the forehead, abdomen, forearm, hand, thigh, calf, and foot, and the mean Tsk was calculated using the Hardy-Dubois formula (Hardy et al., 1938). Blood pressure was measured and recorded on the workload test (W1 and W2) and recovery period (R1 and R2) at the end of walking periods. Blood pressure was measured every 10 minutes by a cuff-type device (HEM 770A, OMRON Co., Tokyo, Japan). HR was monitored and recorded using an RS400 HR monitor (Polar Electro Oy, Finland) throughout the experiment. The Physiological Strain Index (PSI) was calculated using core temperature and HR values measured during work and rest periods, following the formula proposed by Moran et al. (1998), with higher scores indicating greater physiological strain. PSI scores range from 0 (no strain) to 10 (maximal strain), with values of 3–4 indicating moderate strain and values exceeding 5 indicating high strain with an elevated risk of heat illness (Moran et al., 1998; Davey et al., 2021).

Body Balance performance

Balance performance was assessed by postural balance (body sway) tests, functional reach tests, and 2-step tests. Body sway was measured and analyzed using a GS-3000, a force plate, and a system for measuring the center of the pressure (Anima Co., Chou-Fu, Japan). Body sway length and area were

calculated by devices for data analysis. For the body sway test, participants stood on the force plate and were asked to maintain an upright posture for 30 seconds with their eyes open (EO) or eyes closed (EC). Sway length and sway area were recorded from the points when participants closed or opened their eyes.

The functional reach test and 2-step test are simple methods for measuring balance performance. The locations of the hand and shoulder on one side of the body were used as measuring points for the functional reach test. Participants stood and raised one arm straight and parallel to the floor. They were asked to extend their arm forward as far as possible while maintaining balance. The location of the extended arm was recorded as the finish point and was used to calculate distances. For the 2-step test, participants stood at the start line and, when signaled, took two steps forward, maintaining their balance, stepping as far as possible. The distance between their two steps was recorded.

Subjective evaluation

During the experiment, participants were asked to subjectively evaluate their thermal sensation, thermal comfort, fatigue, and thirst using a visual analogue scale from 0 to 10. Subjective evaluation was evaluated using a 10-point visual analog scale (VAS), with scores ranging from 0 (neutral) to 10 (extremely hot, fatigued, and thirsty) without thermal comfort. The thermal comfort was accessed using scale 0 (extremely uncomfortable) to 10 (neutral). Higher scores indicated greater perceived thermal comfort. RPE was assessed using Borg's 6–20 scale.

Data analysis and statistics

A two-way repeated measures analysis of variance (ANOVA) was conducted with trial and time as the main factors. Following the identification of significant F-values, pairwise comparisons were performed using Bonferroni's post hoc correction to determine specific differences between time points. Pearson's correlation coefficient was calculated to examine relationships between postural balance parameters (sway length and area) and physiological measures (Tre and body weight loss). Additionally, Pearson's correlation coefficient was calculated between the Physiological Strain Index (PSI) at the end of W2 and each balance parameter (sway length and sway area under EO and EC conditions) to directly quantify the relationship between physiological strain and balance impairment. Body weight loss was expressed as a percentage of pre-trial body weight (%BW). Subjective evaluation data violated normality assumptions; consequently, the Kruskal-Wallis test was employed for non-parametric analysis. Statistical significance was maintained at $p < .05$ for all analyses. All statistical procedures were conducted using SPSS software (version 27.0; IBM Corp., Armonk, NY).

Results

Physiological responses

Body weight loss results indicated that sweating varied with workload and thermal environment. The body weight loss results according to heat strain and workload were 0.5 ± 0.1kg, 0.5 ± 0.1kg, 0.6 ± 0.2kg, and 1.0 ± 0.3kg, respectively, for W22-LT, W22-HT, W29-LT, and W29-HT. As expected, sweating intensified as temperatures increased. Body weight loss increased significantly at W29-HT, the highest temperature condition, when compared with WBGT 22 ºC conditions ($p < .001$) and W29-LT ($p < .01$). The body weight loss of W29-HT was 1.5% of the participants' mean weight, significantly higher than any other condition (W22-LT: 0.7%, W22-HT: 0.8%, W29-LT: 0.9%).

Similarly, as shown in Fig. 3, in W29-HT, Tre was more strongly elevated from the beginning of W2, the second workload period ($p < .05$). Significant differences were observed among conditions at the end of W2. This elevated tendency was maintained throughout the one-hour recovery time. Mean Tsk was also elevated from the start of the workload test. From the beginning of exercise (W1), significant differences among all conditions were represented in the experimental period ($p < .01$). In particular, the mean Tsk in W29-LT and W29-HT, which assume WBGT 29 ºC, rose sharply immediately after the start of exercise. When all the conditions were compared, the mean Tsk remained higher when the air temperature was high, even within the same WBGT range.

Figure 4 presents the results for HR and PSI. For HR, W29-LT and W29-HT demonstrated significantly higher values than W22-LT at the end of the first workload test ($p < .05$). Additionally, at the completion of the second workload test, HR in W29-LT and W29-HT were significantly elevated compared to both W22-LT and W22-HT. During the recovery period, HR in W22-LT and W22-HT recovered to pre-load values, whereas those in W29-LT and W29-HT remained higher than pre-load values. PSI values, calculated at distinct experimental phases (prior to and following the workload, and at the midpoint and end of the recovery period), are shown in Fig. 4 (right). Across conditions in W2 period, PSI values ranged from 2–3 in W22-LT and W22-HT, 3–4 in W29-LT and W29-HT.

Balance tests

Postural balance measures, including sway length and sway area, generally increased at the end of the workload test (Table 1). Specifically, during EO postural balance tests, sway length and sway area increased significantly following the workload in W29-HT. Additionally, a significant increase in sway area with eyes open was observed in W29-LT when comparing before and after the workload measurements.

Table 1
Body sway length and are results.

		Body sway length (cm)		Body sway area (cm^2)	
		EO	EC	EO	EC
W22-LT	Initial rest	34.0 ± 7.0	42.7 ± 8.9	2.4 ± 1.8	3.2 ± 1.9
	W2	37.0 ± 9.7	48.9 ± 16.5	2.7 ± 1.3	4.8 ± 3.5
	R1	35.2 ± 7.0	50.8 ± 14.7	3.4 ± 2.3	5.7 ± 3.9
	R2	34.9 ± 8.8	44.9 ± 14.2	3.2 ± 1.8	4.2 ± 3.8
W22-HT	Initial rest	30.5 ± 6.7	41.5 ± 8.0	2.3 ± 1.6	3.0 ± 1.8
	W2	39.7 ± 11.9	53.3 ± 20.3	4.2 ± 4.0	5.3 ± 4.1
	R1	36.9 ± 8.2	48.8 ± 16.3	3.5 ± 2.2	5.1 ± 2.9
	R2	33.7 ± 7.1	46.5 ± 8.4	3.0 ± 1.3	4.7 ± 2.7
W29-LT	Initial rest	32.2 ± 7.3	41.5 ± 11.0	1.9 ± 1.1	2.7 ± 1.1
	W2	38.4 ± 11.9	47.3 ± 7.3	3.6 ± 2.3*	4.3 ± 2.4
	R1	32.9 ± 7.6	46.8 ± 10.7	2.8 ± 1.6	4.7 ± 2.4
	R2	34.5 ± 5.8	47.2 ± 10.5	2.5 ± 1.0	4.6 ± 3.2
W29-HT	Initial rest	31.6 ± 5.3	46.6 ± 10.0	2.1 ± 0.8	5.2 ± 5.5
	W2	39.9 ± 10.3*	51.1 ± 24.0	4.7 ± 4.3*	6.1 ± 4.5
	R1	36.3 ± 8.6	56.2 ± 10.3	3.0 ± 1.7	6.4 ± 4.5
	R2	35.7 ± 5.1	48.5 ± 9.4	3.0 ± 1.3	4.3 ± 1.0

* indicates p<.05 between before and after the workload test (Initial rest vs. W2).

EO = eyes open, EC = eyes close

A significant correlation was found between body sway length under EC conditions and Tre (Fig. 5, a), indicating a weak positive linear association ($r = .169$, $p < .05$). Postural balance outcomes also showed statistically significant, modest positive correlations with body weight loss, including sway length with EO ($r = .233$, $p < .05$), sway area with EO ($r = .203$, $p < .05$), sway length with EC ($r = .255$, $p < .01$), and sway area with EC ($r = .216$, $p < .05$; Fig. 5, c - f). In contrast, PSI at the end of W2 demonstrated non-significant positive correlations with both sway length and sway area under EO and EC conditions.

In the functional reach assessment, low-humidity conditions (W22-HT and W29-HT; 40% RH) reduced reach distance following the workload test. In contrast, under high-humidity conditions (W22-LT and W29-LT; 70% RH), reach distance increased immediately after the workload and decreased during the

recovery period (Fig. 6, b). Mean stride lengths from the 2-step test decreased following the workload exposure. In W29-HT, these lengths showed further reduction at the midpoint of the recovery period (Fig. 6, d). However, no significant differences in either measurement were observed between conditions across the temporal progression.

Subjective evaluation

Thermal sensation scores increased significantly during the workload test across all conditions (Fig. 7, left; $p < .01$). While values for W22-LT, W22-HT, and W29-LT returned to baseline during recovery, W29-HT exhibited a secondary elevation in thermal sensation during the recovery period. Thermal comfort scores decreased significantly for all conditions during the workload (Fig. 7, right; $p < .01$), and subsequently improved during recovery in every condition except W29-HT. Participants' self-ratings of RPE, mental fatigue, physical fatigue, and thirst all increased during both the workload and recovery periods; however, no statistically significant differences were observed among conditions (data not shown).

Discussion

This study investigated physiological responses and postural balance performance changes in healthy adult males representing the physical characteristics of industrial workers exposed to physical workload and heat stress. Elevated WBGT levels, particularly those corresponding to 'Severe Warning' conditions (WBGT 29°C), significantly amplified physiological strain and impaired balance performance. A significant positive correlation was observed between physiological strain indicators such as increased Tre and body weight loss and reduced postural stability, emphasizing critical safety implications for workers in hot, humid environments.

Physiological responses

The physiological responses revealed a clear response relation between increasing WBGT levels and the effects of heat and physical strain. W29-LT and W29-HT (WBGT 29°C) consistently produced significantly greater physiological responses than W22-LT and W22-HT (WBGT 22°C). Body weight loss reached 1.5% of participants' body weight in W29-HT, significantly exceeding other conditions and aligning with previous findings showing 1.2% weight loss in hot environments compared to 0.5% in moderate ones (Schlader et al., 2022). Working in hot environments increases the risk of heatstroke via sudden dehydration. Therefore, proactive and scheduled fluid intake is critical for preventing heat illness among susceptible workers.

Tre increased significantly throughout the workload in W29-HT and remained elevated during recovery, with WBGT 29°C conditions showing consistently higher values than WBGT 22°C from the second workload period onward. Similarly, mean Tsk rose sharply in W29-LT and W29-HT immediately after the initiation of exercise and remained higher in conditions with elevated air temperature, even within the same WBGT range. HR, a key indicator of cardiovascular strain, was significantly higher in WBGT 29 (W29-LT and W29-HT) compared to WBGT 22, especially at the end of the workload tests. While HR

returned to pre-test levels under lower WBGT, it did not fully recover in WBGT 29. Although HR declined during recovery in both W29-LT and W29-HT, it remained significantly higher than results of initial rest period and was slightly higher compared with the WBGT 22 condition. This indicates that higher thermal stress delays cardiovascular recovery after workload.

These thermoregulatory and cardiovascular responses indicate a substantial heat load on the body, particularly in the more extreme conditions. Former studies consistently demonstrate that exposure to hot environments, particularly when combined with physical activity, leads to significant increases in core body temperature and HR (Périard et al., 2021). These cardiovascular and thermoregulatory responses align with established research demonstrating that hot environments (40°C, RH 26%) combined with physical activity lead to core and mean Tsk increases of 0.4°C and 7.6°C, respectively, and HR elevations of 12 bpm compared to moderate conditions (Schlader et al., 2022). Similarly, a thermal environment over 32.1°C in simulated construction tasks led to a post-trial higher core temperature and significantly elevated HR (Tan et al., 2025). These responses were markedly higher than those observed in warm (28.1°C) and cool (24.6°C) conditions.

Overall, the PSI values indicated mild to near-moderate physiological strain. However, these values effectively captured a progressive increase in thermal burden as WBGT rose; strain elevated from low levels (PSI 2–3) in tin W22-LT and W22-HT to approaching moderate levels (PSI 3–4) in W29-LT and W29-HT. These results reveal a quantifiable, escalating physiological burden directly tied to the severity of the thermal environment, even with a controlled heat exposure and workload. The elevated PSI (3–4) in WBGT 29 suggests that participants were approaching levels where heat illness risk increases due to disrupted homeostatic processes (Zamanian et al., 2017).

The PSI values observed in this study indicate generally low physiological strain; however, strain increased progressively as WBGT rose, reflecting greater thermal and workload under hotter conditions. The increases WBGT produced measurable elevations in physiological burden, consistent with previous findings showing that PSI is sensitive to changes in thermal stress and responds proportionally to increases in Tre and HR (Ioannou et al., 2022; Moran et al. 1998). The elevated PSI values were likely driven by the combined effects of environmental heat exposure and fluid loss, both of which impair thermoregulatory efficiency. These results highlight the importance of monitoring PSI during prolonged heat exposure, as even modest increases may signal accumulating physiological strain that could elevate health risk under more severe conditions. Although PSI is useful for quantifying overall physiological strain, its reliance on Tre and HR limits its ability to identify individuals who are approaching a thermal tolerance threshold. Davey et al. (2021) suggested that while PSI serves as a valuable thermal index, the dynamic changes in individual physiological responses, specifically the rate of change in Tre, mean Tsk, and HR, indicate a higher risk of acute heat stress (Davey et al., 2021). Thus, real-time, dynamic physiological monitoring and PSI measurement for industrial worker safety may be required for precise assessment.

The persistent physiological and subjective strain observed during recovery in higher heat conditions, such as the elevation of body temperature and HR in W29-LT and W29-HT and the secondary elevation of thermal sensation in W29-HT, suggests persistent cumulative effects on physiological burden. This reduced recovery capacity has critical occupational implications, as workers may begin subsequent tasks while already physiologically compromised, increasing vulnerability to heat stress.

Subjective evaluations indicated that thermal sensation and comfort did not fully recover under the W29-HT condition. This sustained thermal sensation and discomfort were driven by the fact that both Tre and Tsk reached the highest levels in this condition. Furthermore, the experimental protocol precluded behavioral thermoregulation, such as fluid ingestion or removing the long-sleeved and long-pants work suit, thereby severely limiting participants' ability to dissipate the profound heat storage during the resting period. Despite clear physiological and postural deterioration under heat stress, participants' RPE and fatigue did not differ across conditions. This mismatch between objective strain and subjective perception indicates that participants may fail to recognize neuromuscular and sensory impairments due to the workload with heat exposure, emphasizing the need for objective thermal exposure limits and continuous physiological monitoring in occupational environments.

Balance performance impairment

Balance ability refers to the central nervous system's capacity to regulate posture and movement by integrating sensory inputs from the vestibular, visual, and proprioceptive systems. Reduced body balance is commonly linked to decreased muscle flexibility and strength, impaired sensory processing, and delayed motor responses (Peterka, 2002; Yakut and Talu, 2021). Heat exposure, as indicated by WBGT and the resulting physiological strain, can compromise this intricate system through interconnected mechanisms.

Heat stress and hyperthermia substantially disrupt neural activity, compromising cognitive domains such as sustained attention, memory, and executive function[21)]. These deficits can interfere with the neural mechanisms underlying postural control. In addition, elevated brain temperature contributes to central nervous system fatigue, diminishing the ability to maintain maximal motor output and impeding coordinated movement (Khan et al., 2025). This fatigue is a key pathway through which thermal stress disrupts balance ability. Heat exposure exerts considerable cardiovascular strain, characterized by elevated HR and thermoregulatory redistribution of blood flow from core organs to the skin (Nybo, 2010). Reduced blood flow to the brain can contribute to orthostatic intolerance, marked by dizziness and syncope upon standing (Crandall et al., 2010), compromising postural stability and increasing fall risk.

The balance parameter increased across conditions following workload testing with heat exposure, including sway length and area. W29-HT consistently elicited significant increases in sway length and area under eyes-open conditions, with W29-LT also showing substantial sway area increases. These findings indicate progressive degradation of static postural stability as heat exposure intensifies. Despite the limited sample size (n = 10) in the present study, the observed correlation patterns consistently support impaired postural control due to physiological strain from heat exposure and workload. The

significant increases in body sway parameters in WBGT 29°C conditions, contrasted with non-significant differences in functional reach and 2-step tests, suggest that subtle postural sway measurements are more sensitive indicators of heat-induced balance impairment than dynamic balance tests, providing a more precise measure of heat- and workload-related balance impairment.

Heat exposure compromised balance through central nervous system fatigue (Khan et al., 2025), cardiovascular strain affecting cerebral blood flow (Crandall et al, 2007; Nybo, 2010), and impaired sensory integration (Peterka, 2002). These findings align with previous research showing elevated sway velocity and increased sway area and length post-exercise among construction workers in 40°C environments (Schlader et al., 2022). The observed balance impairments are consistent with established effects of mild hyperthermia on sensory integration, leading to increased postural sway and delayed motor responses. Extreme environmental heat degrades the physiological mechanisms underlying postural control. Consequently, recognizing these environmentally induced physical vulnerabilities is essential for mitigating risks such as slips, trips, and falls in thermally demanding occupational settings, such as construction work.

Temperature versus humidity effects on physiological strain

While higher WBGT typically correlates with increased physiological strain, this relation is not always straightforward. This study revealed that temperature effects were more pronounced than humidity effects at equivalent WBGT levels. Physiological responses, such as Tre, mean Tsk, and body weight loss, were significantly higher in high temperature conditions than in low temperature conditions, even at the same WBGT level.

Previous studies have highlighted that high humidity levels significantly increase physiological loads even when WBGT remains consistent. High humidity severely impedes evaporative cooling, the effective heat loss mechanism in hot environments. Claassen and Kok (2007) reported that participants exposed to WBGT 30°C and 32°C with high humidity experienced significantly higher core temperatures and HRs and a reduced tolerance time than those in low humidity conditions. Thus, considering only WBGT can lead to an underestimate of the actual thermal load in high-humidity conditions. However, in this study, we could not verify the effect of humidity at high WBGT levels; the current findings suggest that ambient temperature may be the primary driver of physiological responses.

Practical implications

The present physiological responses were significantly higher in high temperature conditions than in low temperature conditions, even at the same WBGT level. Furthermore, the progression from mild to moderate physical strain corresponded with increasing exposure to high ambient temperature, suggesting that this combination should be further investigated to determine the HR and temperature thresholds for heat stress guidelines, particularly in environments approaching high WBGT. The superior sensitivity of postural sway measurements compared to the dynamic balance test indicates potential for developing more precise heat stress monitoring protocols. The dehydration observed in participants

suggests that proactive fluid intake strategies are essential, and real-time physiological monitoring may be necessary for worker safety in severe thermal conditions.

Study Limitations and Future Directions

This study involved a specific population of healthy young males in controlled laboratory settings, which may limit the applicability and generalizability of the findings to diverse industrial fields. Future research can recruit participants from diverse age, gender, and individual acclimatization groups, as these factors significantly influence heat sensitivity and physiological responses. The use of estimated rather than directly measured WBGT values represents another limitation. Directly measuring WBGT in chamber research would provide more accurate information about the work environment and reveal relationships among temperature, humidity, and physiological strain.

Conclusion

This study investigated the combined effects of environmental heat exposure and physical workload on human physiological responses and postural stability. The findings demonstrate that a high metabolic workload under elevated WBGT conditions compromises thermoregulatory efficiency and impairs static balance control. Notably, physiological strain and postural degradation were significantly more pronounced in conditions characterized by higher ambient temperatures, even at identical WBGT levels. On average, participants lost 1.5% of their body weight, underscoring the risk of dehydration in a hot, humid environment. Tre and mean Tsk, as well as HR, were significantly higher when WBGT was high, and temperatures were higher. PSI also showed the same tendency with increasing physiological strain, particularly as WBGT and temperature increased. Postural balance measurements generally increased during the workload test, and these balance outcomes showed significant correlations with body weight loss, which indicates a degree of dehydration. However, no significant differences were found in functional reach and 2-step tests in all conditions. Thus, the postural balance test is a more effective measurement of heat-induced balance impairment than dynamic balance tests. The strain from physical workload in a hot environment impairs thermoregulation and balance, thereby increasing the risk of workplace accidents.

Declarations

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Authors' contributions

SY is the sole author of this work and was responsible for all aspects of the study, including conceptualization, data analysis, and manuscript preparation.

Data Availability

Research data can be shared only for reasonable reasons. Individual participant data cannot be provided in accordance with ethical guidelines and to protect participant privacy.

Study Funding

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Conflict of Interest

No potential conflict of interest was reported by the author(s).

Ethics approval

This study was reviewed and approved by the National Institute of Occupational Safety and Health, Japan (H2616). All research procedures complied with relevant ethical guidelines and regulations.

Consent to participate

All participants were fully informed about the study procedures and provided written informed consent prior to participation.

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Figures

Figure 1

The clothing condition during the experiment

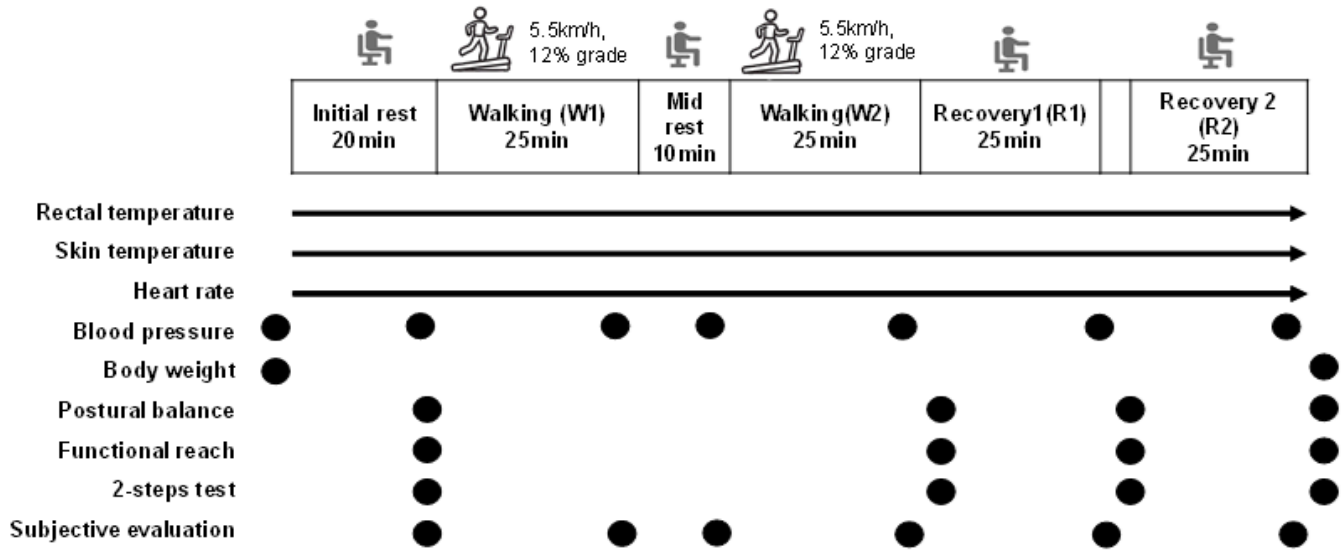

Figure 2

The experiment protocol

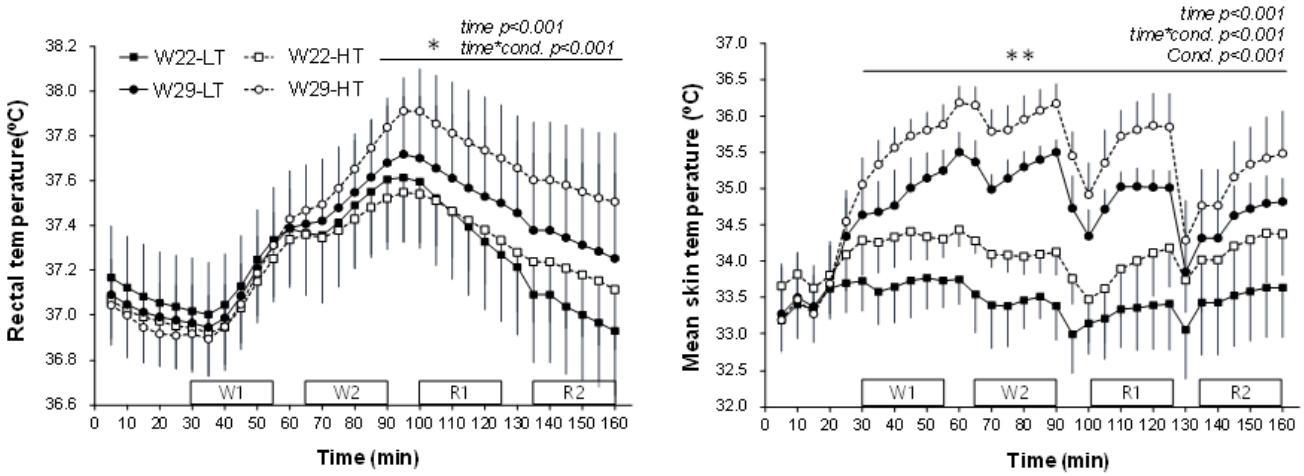

Figure 3

Temporal changes in rectal temperature (left) and mean skin temperature(right) over the experimental period. * and ** indicate statistically significant differences at $p < 0.05$ and $p < 0.01$ between all conditions.

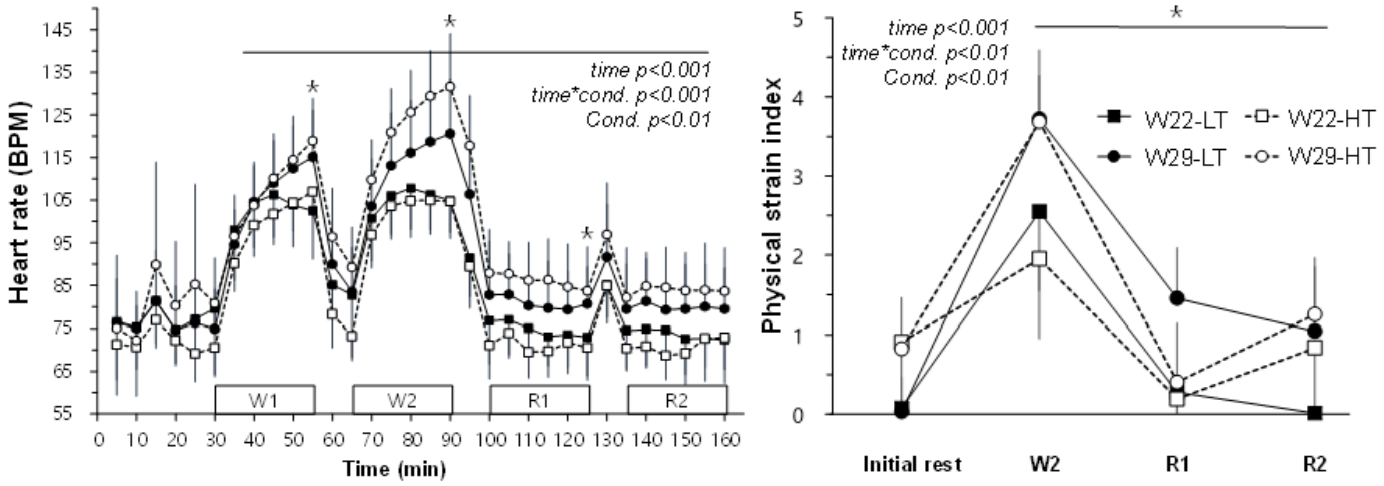

Figure 4

Temporal changes in heart rate (left) and physiological strain index (right) over the experimental period. * indicates statistically significant differences at $p < 0.05$ between all conditions.

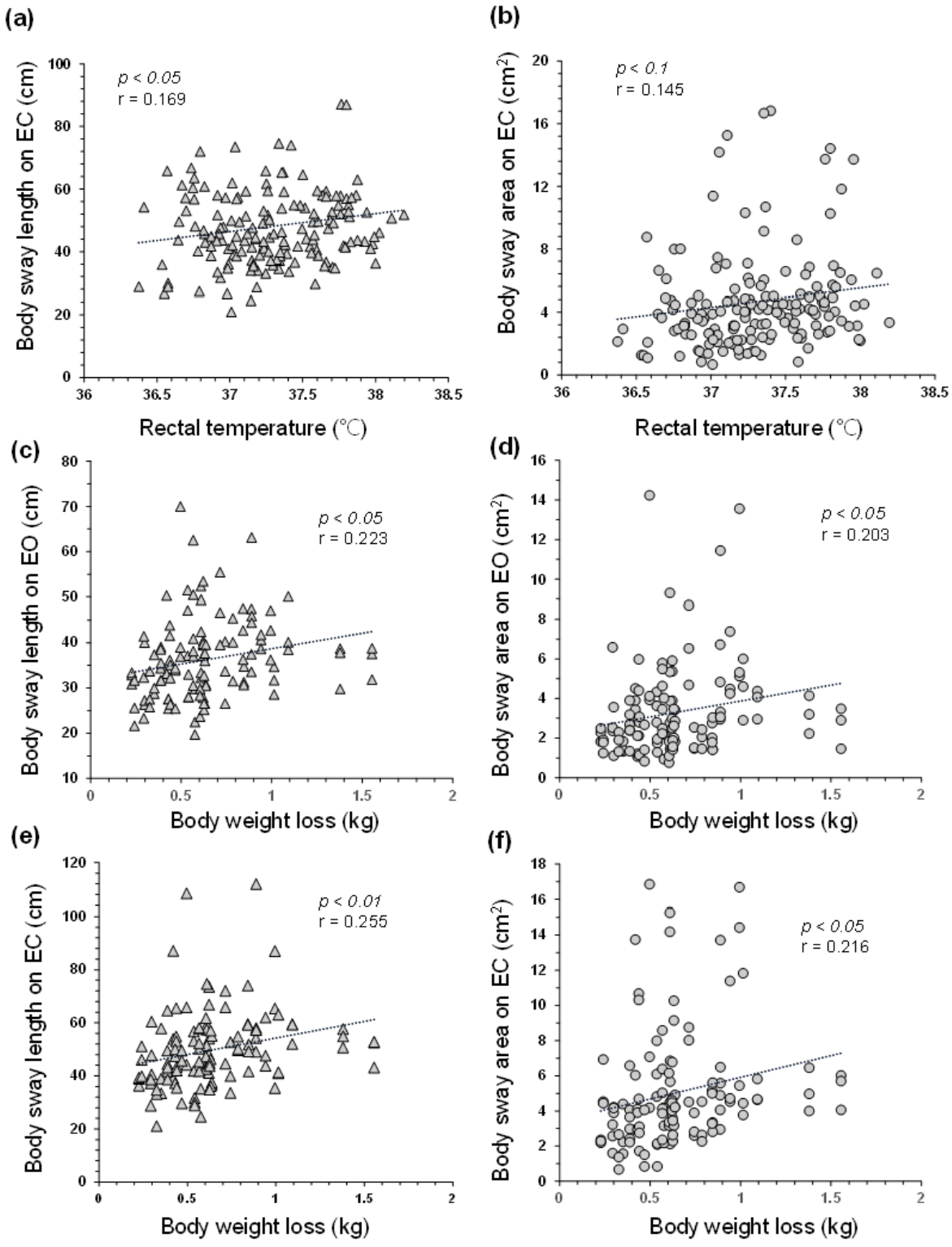

Figure 5

The correlations between postural balance measures and physiological indicators: (a) Body sway length with eyes closed and rectal temperature, (b) Body sway area with eyes closed and rectal temperature, (c) Body sway length with eyes open and body weight loss (d) Body sway area with eyes open and body weight loss, (e) Body sway length with eyes closed and body weight loss, (f) Body sway area with eyes closed and body weight loss

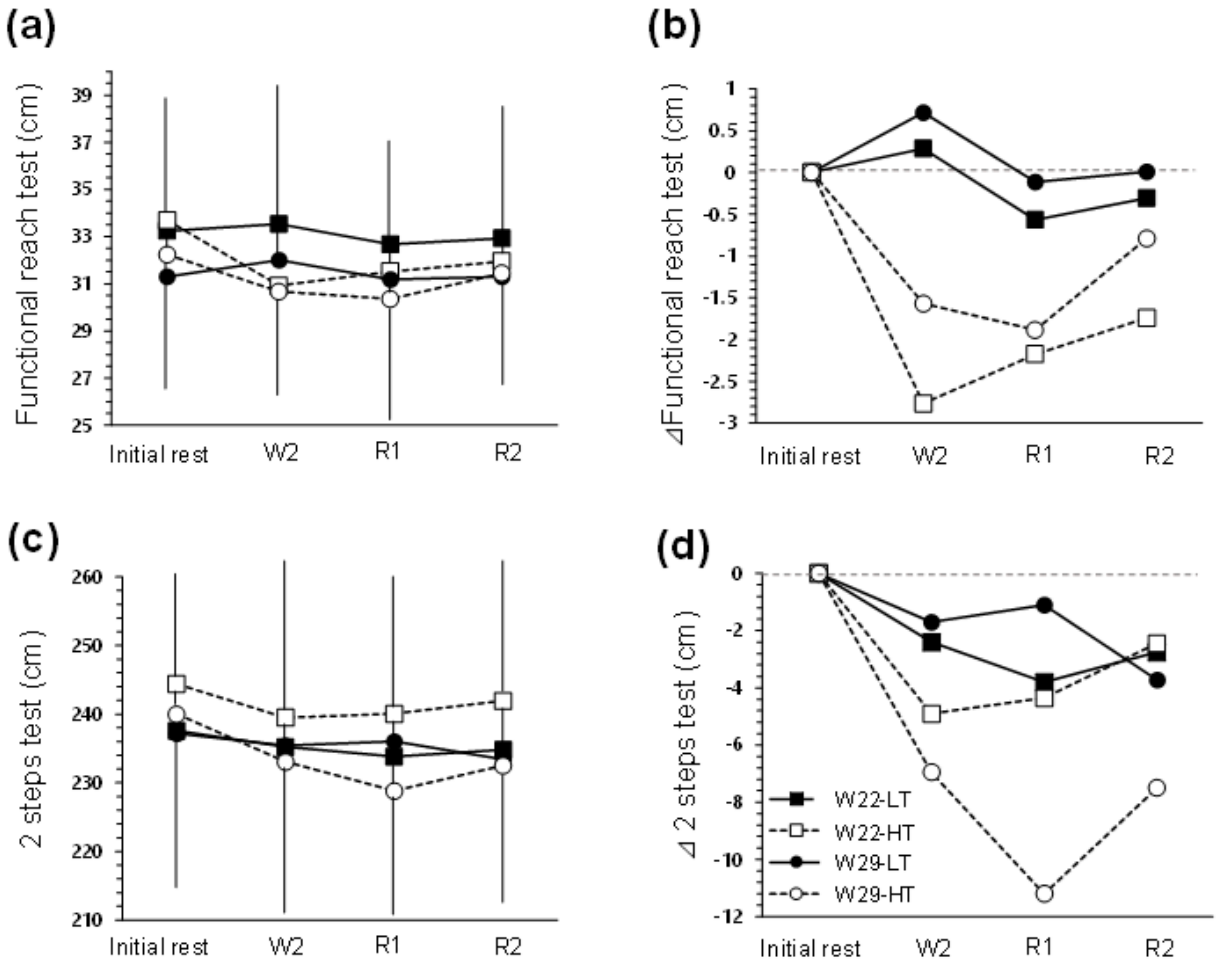

Figure 6

Body balance performance test results: (a) Functional balance test, (b) Delta values of the functional balance test, (c) 2-steps test, and (d) Delta values of the 2-steps test.

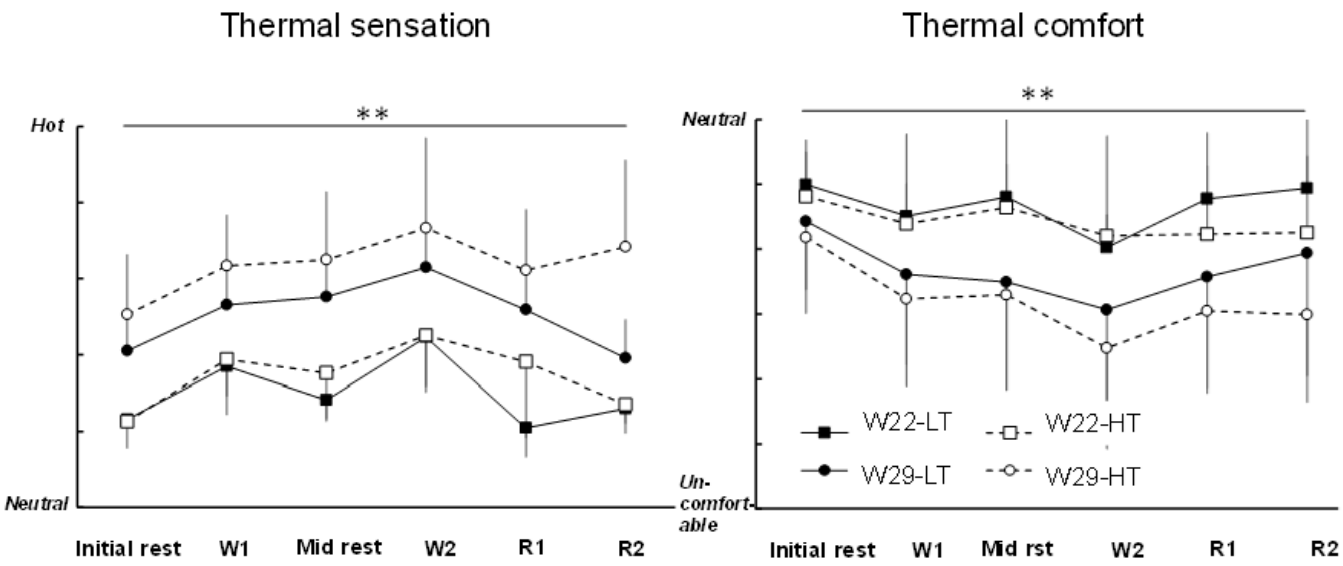

Figure 7

Self-rating scores of thermal sensation (left) and thermal comfort (right). ** indicates statistically significant differences among all conditions at $p < 0.01$.