Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Adaptive Differences in Cutaneous Thermal Sensations across Natural Climates: Cold, Temperate, and Tropical indigenes

Sang-Hyun Roh
Syifa Salsabila
Titis Wijayanto
Joo-Young Lee
leex3140@snu.ac.kr

Seoul National University https://orcid.org/0000-0002-5208-0941

Research Article

Keywords: Heat acclimatization, Thermal threshold, Thermal sensitivity, Contact heating, Radiant heating

Posted Date: June 26th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9485028/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Abstract

The purpose of this study was to investigate the adaptive differences acquired by natural climates on cutaneous thermal sensations in tropical, temperate, and cold indigenes. Fourteen Indonesians (tropical), 15 Koreans (temperate), and 12 Mongolians (cold) participated for the contact heat test. Fourteen Indonesians and 14 Mongolians participated for radiant heat test. Cutaneous warmth, hot, and heat pain sensations were measured on 17 body regions. Thermal stimulator (6.25 cm2) was used to contact stimuli and surface temperature increased by 0.1oC/s. Radiant stimuli was imposed with radiant heat panel (100 cm2) and set to increase the surface temperature at a constant rate of 1oC/s. The results showed that Indonesians had significantly higher cutaneous thermal thresholds (higher Tsk at thermal sensations) and thermal insensitivity (high ΔTsk for thermal thresholds) than Mongolians (cold) in both heat stimuli ($P<0.05$). For contact heat, these group differences were prevalent over all body regions except the upper arm. Koreans had an intermediate level of thermal sensitivity, showing higher thermal sensitivity than Indonesians but lower sensitivity than Mongolians. For radiant heat, group differences in thermal thresholds were pronounced in the trunk and distal legs, while Indonesians showed significantly higher thermal sensitivity over a broader range of body regions than Mongolians. Furthermore, the most extensive group differences were observed for hot sensation rather than warmth or heat pain levels. In summary, these findings suggest that long-term exposure to natural climate can modify cutaneous thermal sensations among indigenes of tropical, temperature and cold regions, even for populations living in modernized environments.

Introduction

Repeated exposure to heat is known to lead various physiological changes and thermoregulatory responses. Heat acclimation is a physiological adaptation which is achieved through relatively short-term heat exposure, typically within days or weeks, and is often conducted in a laboratory or artificial chamber (Daanen et al., 2018). Thermoregulatory benefits of heat acclimation can be seen in reduced rectal temperature and heart rate, along with improved exercise performance in hot environment (Garrett et al., 2009; Ko et al., 2020a). Furthermore, heat acclimation programs can elicit physiological improvements, such as increased maximal oxygen uptake ($VO2_{max}$), elevated lactate threshold, and expanded plasma volume (Lorenzo et al., 2010). An increased sweat rate and lower rectal temperature at the onset of sweating suggest that sweating sensitivity is enhanced as the results of heat acclimation (Ko et al., 2020b; Shvartz et al., 1979). While short-term heat acclimation induces several changes in thermoregulatory system to enhance heat dissipation, these benefits gradually diminish within a few days or weeks once heat exposure is discontinued (Garrett et al., 2011; Pandolf, 1998).

Heat acclimatization, on the other hand, consists of adaptive physiological and behavioral changes occurring over the lifetime of an organism to reduce the strain caused by stressful changes in the natural climate (IUPS, 2001). It is reasonable to assume that tropical indigenes are exposed to heat more frequently over the lifetime than temperate or cold indigenes. The distinct physiological responses induced by natural climates have been investigated in previous studies. Tropical indigenes were more tolerant to heat stress, exhibiting a delayed onset time of sweating and a lower local sweat rate (Matsumoto et al., 1993). Furthermore, differences in thermoregulatory responses indicate that tropical males effectively resist dehydration through a lower local sweat rate and lower heat-activated sweat gland density in a hot environment (Saat et al., 2005). Such increased sweating resistance, characterized by a lower sweat rate, active sweat gland density, and sweat output per gland, is found in tropical indigenes and is considered an efficient maintenance of body fluids (Lee et al., 2009). Characteristics of sweating tolerance acquired through natural climate exposure gradually decay over years, however, it remained longer than physiological changes obtained by short-term heat acclimation (Bae et al., 2006). Wakabayashi et al. (2011) showed that tropical indigenes had higher rectal temperature than temperate indigenes at rest, but increase of rectal temperature was suppressed during exercise, suggesting that tropical indigenes had superior heat tolerance with enhanced heat dissipation.

While thermoregulatory changes induced by long-term exposure to natural climates have been extensively investigated, the significant effects of heat acclimatization on cutaneous thermal sensations have been relatively neglected. As the outermost layer of human body, skin is the primary site for heat exchange with the environment and used as feed-forward signal for thermoregulation. Thermal sensation and comfort are determined by skin temperature and these subjective responses drive thermoregulatory behavior before significant changes in core temperature occur (Gagge et al., 1967; Schlader et al., 2011). There were several efforts to explore the ethnic or racial differences in cutaneous pain perception. Sheffield et al. (2000) reported that African Americans perceived thermal stimuli as more painful than Caucasians. Watson et al. (2005) demonstrated that South Asian males had lower heat pain thresholds and more sensitive to heat stimuli than White British males. However, since these subjects resided in the same geographical region, these ethnic differences cannot be fully attributed to understand the effects of long-term exposure to distinct natural climates.

To date, few studies have investigated the adaptive difference of cutaneous thermal sensations resulting from natural climate. Lee et al. (2010) investigated the effect of heat acclimatization on the cutaneous thermal sensations. They reported that tropical males perceived warmth at a higher skin temperature than temperate males. Furthermore, tropical indigenes were, on average, 3.5^{o}C less sensitive to hot sensations than temperate indigenes, and the characteristics of cutaneous thermal sensation for tropical males were retained even though they resided in temperate climates for up to 61 months (Lee et al., 2011). While it is recognized that cutaneous thermal sensations are influenced by long-term exposure to natural climates, a more comprehensive understanding of the adaptive differences in cutaneous thermal sensations resulting from heat acclimatization is still required. To the best of our knowledge, no previous studies have investigated cutaneous thermal sensations across native populations from tropical, temperate, and cold climates simultaneously. For these reasons, we investigated cutaneous warmth, hot, and heat pain sensations induced by contact and radiant heat sources among tropical, temperate, and cold indigenes in overall body regions.

Methods

Cutaneous thermal sensations from contact heat were measured among Indonesians (tropical), Koreans (temperate), and Mongolians (cold), whereas radiant heat was tested for Indonesians (tropical) and Mongolians (cold). To minimize seasonal variations, experiments were conducted during the warmest months in each location: Yogyakarta, Indonesia (January to February; hot and humid), Seoul, Korea (June to August; summer), and Ulaanbaatar, Mongolia (July to August; summer). Individuals with skin diseases were excluded during the screening stage, and all participants provided voluntary consent forms before participating. Subjects were instructed to abstain from strenuous exercise and alcohol for 24 h, and to avoid consuming food and caffeine for 3 h before each trial. When the subjects arrived at the experimental room, they changed into standardized clothing (underwear, long pants, and a long-sleeve T-shirts) and rested for 30 min to ensure physiological stabilization. During the experiments, a native speaker was involved to assist with interpretation for the subjects. The experimental protocols were approved by the Institutional Review Board of Seoul National University (IRB No. 2207/002–008). All procedures were conducted in accordance with the Declaration of Helsinki, and written informed consent was obtained from all subjects prior to participation.

Experiment 1 - Contact heat

Subjects

A total of 41 healthy males participated in the contact heat test: 14 Indonesians (age: 20.9 ± 0.8 y; height: 171.2 ± 6.0 cm; body weight: 70.9 ± 16.5 kg; BMI: 24.1 ± 4.8 kg/m^2), 15 Koreans (age: 23.7 ± 1.8 y, height: 175.1 ± 5.6 cm, weight: 78.7 ± 17.8 kg, BMI: 25.7 ± 6.1 kg/m^2), and 12 Mongolians (age: 21.2 ± 1.7 y; height: 175.6 ± 5.6 cm: weight: 74.1 ± 8.9 kg; BMI: 24.0 ± 2.7 kg/m^2). Statistical analysis showed that the Indonesian and Mongolian subjects were significantly younger than the Korean subjects ($P < 0.001$). There were no significant differences in height, weight, and BMI among the three groups. The data of the Korean males were obtained from proceeding research by our team with same experimental protocol.

Experimental procedure and measurements

Seventeen body regions (the forehead, neck, chest, upper back, abdomen, waist, upper arm, forearm, hand, palm, buttock, front thigh, shin, back thigh, calf, foot, and sole) were stimulated using a thermal stimulator (Intercross-210, Intercross Co., Japan). The order of measured body regions was randomized. The probe of the thermal stimulator (surface area: 6.25 cm^2) was placed on the skin in the direction of gravity, and artificial pressure was not applied to the probe. The surface temperature of the probe was set to increase at a constant rate of 0.1^{o}C/s (*Method of limit*), starting from the point where the heat flux between the probe and skin was zero. For safety, the maximum temperature was limited to 50^{o}C. Subjects pressed a button switch to record the probe surface temperature when they initially perceived warmth, heat, and heat pain sensations. Participants performed several training sessions before the main trials to clearly familiarize to identifying warmth, hot, and heat pain sensations. To maintain a thermally neutral state, the experimental room conditions were maintained at 23.9 ± 0.4^{o}C and 51 ± 8%RH for Indonesians, 24.7 ± 0.2^{o}C and 52 ± 3%RH for Koreans, and 24.5 ± 0.3^{o}C and 49 ± 2%RH for Mongolians.

Experiment 2 - Radiant heat

Subjects

A total of 28 healthy males participated in the radiant heat test: 14 Indonesians (age: 20.9 ± 0.8 y; height: 171.2 ± 6.0 cm; body weight: 70.9 ± 16.5 kg; BMI: 24.1 ± 4.8 kg/m^2) and 14 Mongolians (age: 21.5 ± 2.2 y, height: 174.6 ± 6.2 cm, weight: 72.9 ± 8.7 kg, BMI: 23.8 ± 2.6 kg/m^2). No significant differences in age, height, weight, and BMI were found between the Indonesian and Mongolian groups.

Experimental procedure and measurements

Cutaneous thermal sensations stimulated by radiant heat were tested in 17 body regions. The local skin temperature (T_{sk}) of the stimulated regions was measured in 1-s intervals using a thermometer (LT-ST08-12, Gram Ltd., Japan; precision: ± 0.01^oC) and recorded with a data logger (LT-8A, Gram Ltd., Japan). The surface area of the radiant heat panel was 100 cm^2 (10 cm ×10 cm) and was maintained at a constant distance of 10 cm from the skin. The radiant heat panel was connected to DC power supply (Model 2260B-80-27, Keithley, USA) and set to increase the surface temperature at a constant rate of 1^oC/s (Method of Limit), starting from a baseline of 35^oC. For safety and technical specification of the device, the maximum temperature was limited to 230^oC. The T_{sk} was recorded at the moment of subjects initially felt warmth, hot, and heat pain sensations was recorded. In cases of subjects did not respond cutaneous thermal sensations before the radiant heat panel reached 230^oC, the T_{sk} at the maximum temperature was used as the representative thermal thresholds. The experimental room was maintained under thermally neural conditions in 24.1 ± 0.3^oC and 52 ± 7%RH for the Indonesians, 24.3 ± 0.3^oC and 48 ± 2%RH for the Mongolians.

Data analysis

All measurements were repeated three times for each body region, and the results are presented as mean ± standard deviation (SD). Statistical analyses were performed using SPSS v.26.0. To identify statistical differences among the Indonesian, Korean, and Mongolian groups in the contact heat test, one-way analysis of variance (ANOVA) was used and Duncan's Post-hoc test was carried out for group comparisons. For the radiant heat test, an independent-samples t-test was used to analyze group differences between the Indonesian and Mongolian groups. Statistical significance was set at $P < 0.05$. Initial skin temperature and thermal thresholds of the whole body were calculated using [Eq. 1], based on the surface area of the respective body regions (Lee, 2005).

Whole body thermal threshold = $0.075T_{Forehead} + 0.015T_{Neck} + 0.088T_{Chest} + 0.061T_{Upper\ back} + 0.086T_{Abdomen} + 0.035T_{Waist} + 0.087T_{Upper\ arm} + 0.062T_{Forearm} + 0.025T_{Hand} + 0.025T_{Palm} + 0.087T_{Buttock} + 0.075T_{Front\ thigh} + 0.069T_{Shin} + 0.074T_{Back\ thigh} + 0.068T_{Calf} + 0.034T_{Foot} + 0.034T_{Sole}$

[Eq. 1]

Results

Experiment 1 – Contact heat

Whole body thermal thresholds in response to contact heat

While the initial mean skin temperature (_T_{sk}) over the whole body was relatively similar among the three groups, Mongolians (32.4 ± 0.3^oC) showed a slightly but significantly higher than Indonesians (32.1 ± 0.3^oC) and Koreans (31.9 ± 0.4^oC) ($P < 0.01$, Fig. 1). In contrast, Indonesians had the highest whole body thermal thresholds, followed by Koreans and Mongolians. For the warmth thresholds, Indonesians (39.3 ± 1.8^oC) showed significant differences compared to Koreans (38.1 ± 1.4^oC) and Mongolians (37.2 ± 1.1^oC) ($P < 0.01$). Regarding hot thresholds, there were significant differences among the Indonesians (43.6 ± 2.5^oC), Koreans (42.1 ± 1.9^oC), and Mongolians (40.5 ± 1.4^oC) ($P < 0.001$). Moreover, Indonesians (47.0 ± 2.2^oC) also showed significantly higher heat pain thresholds than the Koreans (45.1 ± 2.1^oC) and Mongolians (44.3 ± 2.2^oC) ($P < 0.01$).

Regional distribution of initial skin temperature and thermal thresholds

The regional distribution of initial T_{sk} and thermal thresholds (warmth, hot, and heat pain) exhibited distinct patterns among the three groups (Fig. 2). Regarding the initial T_{sk}, Mongolians showed significantly higher temperatures on the 3 body regions (forehead, hand, palm) than Indonesians, 4 body regions (neck, front thigh, back thigh, calf) than Koreans, and 4 body regions (waist, forearm, shin, foot) than Indonesians and Koreans ($P < 0.05$). It was particularly remarkable in the distal regions, where the T_{sk} of each distal region in Mongolians was approximately 1^oC higher than that of Indonesians or Koreans (Fig. 2a). Despite these higher T_{sk} at rest, Mongolians

consistently showed the lowest thermal thresholds, whereas Indonesians showed the highest thermal thresholds on various body regions (Fig. 2, 3). For warmth thresholds, significant group differences were found on the forehead, chest, upper back, abdomen, buttock, front thigh, shin, back thigh, calf, and foot (Fig. 2b). The most frequent differences were observed in hot thresholds, where Indonesians showed significantly higher values in 15 body regions (Fig. 2c). For heat pain thresholds, significant differences were found on the 14 body regions (Fig. 2d). In contrast, the upper arm and palm showed no significant differences in any thermal threshold among the three groups (Fig. 2b, c, d). Thermal body mapping illustrated that regional warmth, hot, and pain thresholds of Indonesians were higher than those of Koreans and Mongolians (Fig. 3).

Comparison of temperature increment (ΔT_{sk}) to contact heat thresholds

The temperature increment from the initial T_{sk} to each thermal threshold (ΔT_{sk}) was calculated to clarify thermal sensitivity. The ΔT_{sk} for each thermal threshold was consistently highest in Indonesians and lowest in Mongolians (Fig. 4). For warmth thresholds, Indonesians required a significantly greater temperature increase in 12 body regions (forehead, neck, chest, upper back, abdomen, waist, hand, palm, buttock, front thigh, shin, back thigh, and foot) (Fig. 4a). Regarding hot thresholds, Indonesians showed significantly higher ΔT_{sk} on overall body regions except upper arm (Fig. 4b). The ΔT_{sk} for heat pain threshold, Indonesians were significantly higher on the 14 body regions (the forehead, neck, chest, upper back, abdomen, waist, forearm, hand, front of thigh, shin, back of thigh, calf, foot, and sole) (Fig. 4c). Mongolians were significantly more thermally sensitive across most body regions, whereas Koreans showed intermediate level of cutaneous thermal sensitivity between Indonesians and Mongolians. Notably, the ΔT_{sk} for each thermal threshold of the upper arm showed no significant differences among Indonesians, Koreans, and Mongolians.

Experiment 2 – Radiant heat

Non-responder up to maximum heating

Non-responder in which subjects did not perceive thermal sensations even at the upper limit temperature of the heating panel (230°C) were more prevalent among Indonesians than Mongolians (Table 1). All of the Mongolian subjects perceived warmth and hot sensations on the overall body regions, while substantial number of Indonesian subjects were non-responder, particularly for hot sensation. Furthermore, more than half of the Indonesian subjects did not report heat pain sensation, whereas more than half of Mongolian subjects perceived heat pain sensation within the safety limit. In cases of subjects did not respond cutaneous thermal sensations before the radiant heat panel reached 230°C, the T_{sk} at the maximum temperature was used as the representative thermal thresholds.

Table 1

Non-responder up to reaching the upper limit temperature of heating panel (230°C) for Indonesians (N = 14) and Mongolians (N = 14)

		Body region																
		FH	NK	CH	UB	AB	WA	UA	FA	HD	PM	BT	TH_F	SH	TH_B	CF	FT	SL
Warmth	Indonesians	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4
	Mongolians	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hot	Indonesians	1	3	2	4	3	6	2	3	6	4	3	4	4	2	4	9	11
	Mongolians	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Heat pain	Indonesians	5	6	7	10	9	9	9	7	12	9	9	13	12	7	9	13	13
	Mongolians	1	0	1	4	4	1	5	0	2	0	2	3	4	1	4	6	6

Whole body thermal thresholds in response to radiant heat

The initial _T_{sk} and thermal thresholds over whole body under radiant heat stimulation are presented in Fig. 5. The initial _T_{sk} was 32.5 ± 0.4°C for Indonesians and 32.7 ± 0.5°C for Mongolians (P = 0.233). Whole body warmth thresholds of Indonesians and Mongolians were 34.4 ± 1.0°C and 33.8 ± 0.6°C, respectively (P = 0.91). Hot thresholds were significantly higher in Indonesians (36.3 ± 1.3°C) than Mongolians (35.0 ± 0.7°C) (P < 0.01). Heat pain thresholds were 37.5 ± 0.9°C for Indonesians and 36.8 ± 1.2°C for Mongolians (P = 0.104).

Regional distribution of radiant heat thresholds among Indonesians and Mongolians

Regarding the initial T_{sk}, Mongolians had significantly higher temperatures than for Indonesians on the forearm (33.3 ± 0.4^{o}C vs. 32.2 ± 0.8^{o}C), hand (32.8 ± 0.7^{o}C vs. 30.9 ± 1.3^{o}C), palm (33.2 ± 0.7^{o}C vs. 31.5 ± 1.4^{o}C), and foot (31.2 ± 1.3^{o}C vs. 28.4 ± 1.3^{o}C) (Fig. 6a). Despite these higher T_{sk} at rest, Mongolians perceived thermal sensations at the T_{sk} compared to Indonesians on the various body regions. For warmth thresholds, Indonesians showed significantly higher on the chest, upper back, abdomen, waist, buttock, front thigh, shin, and back thigh (Fig. 6b). The most frequent differences were found at the hot thresholds on the 9 body regions (chest, upper back, abdomen, waist, buttock, front thigh, shin, back thigh, and calf) (Fig. 6c). For heat pain thresholds, significant differences were observed on the chest, waist, buttock, and front thigh (Fig. 6d). Regional differences in thermal thresholds between Indonesians and Mongolians were prevalent in the trunk and distal legs. Similar to the contact heat results, upper arm and palm showed no significant differences in any of the radiant heat thresholds. Thermal body mapping illustrated that regional warmth, hot, and pain thresholds of Indonesians were higher than those of Mongolians (Fig. 7).

Comparison of skin temperature increment (ΔT_{sk}) to radiant heat thresholds

Surface temperature of the radiant heating panel at the thermal thresholds was higher for Indonesians than for Mongolians (Fig. 8). The ΔT_{sk} showed significant group differences across a broader range of body regions compared to the T_{sk} at thermal sensations (Fig. 6, 8). For the warmth threshold, Indonesians required higher skin temperature increment than Mongolians on the chest, upper back, abdomen, waist, forearm, hand, palm, front thigh, shin, back thigh, foot, and sole (Fig. 8a). It was more evident at the hot threshold, Indonesians had higher ΔT_{sk} on the overall body regions (Fig. 8b). The ΔT_{sk} for heat pain sensation was significantly different on the forehead, chest, upper back, waist, hand, palm, front thigh, shin, foot, and sole (Fig. 8c).

Discussion

The present study has two methodological strengths. First, to our knowledge, this is the first study to simultaneously compare cutaneous thermal thresholds among tropical, temperate, and cold-climate populations. Second, by measuring warmth, hot, and heat pain thresholds across 17 body regions, this study provides the first whole-body mapping of cutaneous thermal thresholds. Based on these methodological strengths, the primary finding of the present study is that Indonesians (tropical) exhibited significantly higher cutaneous thermal thresholds (higher T_{sk} at thermal sensations) and thermally insensitive (high ΔT_{sk} for the thermal thresholds) than Mongolians (cold). For both contact and radiant heat stimuli, the most extensive group differences were observed at the hot sensation rather than warmth or heat pain levels. Furthermore, an interesting observation is that Koreans (temperate) had an intermediate level of thermal sensitivity which they showed lower thermal thresholds and higher thermal sensitivity than Indonesians, whereas had higher thermal thresholds and lower sensitivity than Mongolians. These results suggest that perception of cutaneous thermal sensations could be developed characteristics dependent on long-term exposure to natural climate.

Repeated and prolonged exposure to heat has been reported to induce several changes in thermo-physiological responses. Relatively short-term heat exposure, within days or weeks, improves human thermoregulatory responses (heat acclimation). Increased sweat rate and enhanced sweat sensitivity facilitate heat dissipation, which is associated with reduced rectal temperatures in hot environment (Garrett et al., 2011; Shvartz et al., 1979). Furthermore, heat acclimation induces adaptive changes in subjective thermal perceptions. Young males who performed 10-day heat acclimation training showed lower hot sensations than before training (Ko et al., 2020a; Ko et al., 2020b). Thermoregulatory characteristics, which aim to reduce heat strain developed over a lifetime of human through exposure to natural climates (heat acclimatization). Heat acclimatized tropical indigenes are more tolerable to heat stress and effectively resisted dehydration in hot environment (Lee et al., 2009; Matsumoto et al., 1993; Saat et al., 2005). The effect of heat acclimatization on thermoregulatory behavior has been extensively investigated, but such studies on its specific effect on cutaneous thermal sensations remain scare. Few studies showed that tropical indigenes are less sensitive to perceive cutaneous thermal sensation than temperate indigenes. Malaysians (tropical) had higher warmth thresholds and less sensitive in detecting warm sensations than Japanese (temperate), and inter-threshold zone between warmth and coolness was wider in Malaysians than Japanese (Lee et al., 2010). Furthermore, cutaneous sensory adaptation for heat stimulus in tropical indigenes were retained even after residing in a temperate climate for 5 to 61 months, as they remained less sensitive to warmth, hot, cool and cold sensations than temperate indigenes (Lee et al., 2011). To the best of our knowledge, as no previous studies have investigated cutaneous thermal sensations specially including

cold-climate populations, the results of present study provide essential baseline data for understanding thermoregulation behavior of cold indigenes.

Differences in cutaneous thermal sensations stimulated by contact heat showed that Koreans were thermally more sensitive than Indonesians, but less sensitive than Mongolians. In this regard, although radiant heat was tested only for Indonesians and Mongolians, it is speculated that Koreans might possess an intermediate level of cutaneous thermal sensitivity between Indonesians and Mongolians. Our research team previously investigated warmth and hotness sensations in Korean males by radiant heat (Kwon et al., 2023), but the results showed lower thermal thresholds even than those of Indonesians and Mongolians in the present study. For example, the whole body thermal thresholds of Koreans (warmth: 32.6 ± 1.9^{o}C, hot: 33.2 ± 1.9^{o}C) were lower than those of Indonesians (34.4 ± 1.0^{o}C and 36.3 ± 1.3^{o}C) and Mongolians (33.8 ± 0.6^{o}C and 35.0 ± 0.7^{o}C). Moreover, the values of regional thermal thresholds were also lower for Koreans than for Mongolians. This discrepancy is supposed from seasonal effects of the measurements which Koreans were tested in winter (November to December) (Kwon et al., 2023), whereas Indonesians were tested between January and February (hot and humid) and Mongolians in July to August (Summer) in present study. Human thermoregulatory characteristics have been reported to have seasonal variations. Umemiya (2006) found decreased tympanic temperature, lower metabolic rate, lower body fat, and higher thigh skin temperature in summer than in winter under identical heat stress. Furthermore, mean skin temperature is maintained higher during the summer than winter season and it is linearly related with daily air temperature (Nakamura and Okamura, 1998). Seasonal adaptation is also evident in thermal perceptions, as subjectively neutral and preferred temperature of individuals are lower in cool seasons than hot seasons (Lin et al., 2011; Liu et al., 2017). Indeed, individuals in indoors tend to perceive warmer thermal sensations in winter even when room temperatures are lower than those in summer (Oseland, 1994).

Cutaneous sensory innervation is fundamentally related to nerve fibers which deliver electrical signals from the stimulated skin. Consequently, the density of intra-epidermal nerve fiber (IENF) is closely related to cutaneous thermal sensations (Lauria et al., 2009; McArthur et al., 1998). For example, the forehead was thermally sensitive body region, while the foot and sole were relatively insensitive in the present study. It is consistent with evidence indicating that the face is one of the area with the highest IENF density, while peripheral parts such as the legs or feet have lower IENF density than other parts (Besné et al., 2002; Kawakami et al., 2001). To clarify the effect of heat acclimatization on cutaneous thermal sensations, it is necessary to consider potential ethnic differences in epidermal innervation. Reilly et al. (1997) analyzed the properties and biochemical content of sensory nerve fibers from European Caucasian, Japanese, and Chinese subjects but found no difference in epidermal innervation. IENF density of the thigh and distal part of the leg did not observe differences by ethnicity (McArthur et al., 1998). These findings that characteristics of IENF remain similar regardless of ethnicity reinforced our hypothesis that differences in cutaneous thermal sensations are primarily derived from long-term heat acclimatization rather than innate biological variations.

Most proportion of Indonesian subjects did not perceive hot and heat pain sensations even up to the limit temperature of radiant heating. Considering these non-responder, the actual hot and heat pain thresholds for Indonesians are likely even higher than the results of present study and might be more insensitive than Mongolians. A limitation of the present study is that cutaneous sensations in response to cold stimuli were not investigated. Transient receptor potential melastatin 8 (TRPM8) is known as a cold receptor and also responds to menthol which triggers cool sensations (Johnson et al., 2009). Although research on cold adaptation is less conclusive than that on heat adaptation, thermoregulatory responses to cold appear to be characterized by habituation (blunted shivering and vasoconstrictor responses) as well as metabolic (pronounced thermogenic response), and insulative (enhanced body heat conservation) adaptations (Castellani and Young, 2016; Daanen and Van Marken Lichtenbelt, 2016). An early study showed that cold adapted Inuits showed higher rates of oxygen uptake in comfortable environments, lower increases in resting metabolic rate in cold with less shivering, and quicker hand rewarming during exercise than unadapted males to cold (Andersen et al., 1963). Furthermore, habituation of thermal sensations was found that subjects perceived cold air as less severe following repeated exposure (Leppaluoto et al., 2001). Therefore, it is speculated that cutaneous thermal sensations for cold stimuli may differ significantly among indigenes residing in different climates.

Conclusions

This study is the first to demonstrate climate-dependent differences in cutaneous heat perception across the entire body. We provide evidence that long-term exposure to natural climates (heat acclimatization) induces desensitization of the cutaneous thermal sensations. By measuring thermal thresholds across 17 body regions, this study also provides a whole-body thermal mapping of cutaneous thermal thresholds among populations living in different climatic environments. The primary findings are summarized as follows. First, contact heat: Indonesians residing in tropical climate exhibited the highest thermal thresholds and the greatest thermal

insensitivity (higher ΔT_{sk}) for warmth, hot, and heat pain sensations compared to Mongolians residing in a cold climate. Koreans (temperate) had an intermediate level of thermal thresholds and sensitivity. These group differences were observed across all body regions except upper arm. Second, radiant heat: Indonesians (tropical) exhibited remarkably higher thermal thresholds than Mongolians (cold) in the trunk and distal legs regions. Furthermore, Indonesians were thermally less sensitive (higher ΔT_{sk}) across a broader range of body regions than Mongolians. Third, for both contact and radiant heat stimuli, the most extensive group differences were observed at the hot sensation rather than warmth or heat pain levels. This suggests that the physiological desensitization resulting from heat acclimatization is not uniform across all cutaneous thermal sensation levels, instead, it is most clearly manifested in the perception of intense heat, appearing over the non-noxious (warmth) level but before reaching noxious (heat pain) sensation. These findings may improve our understanding of behavioral thermoregulation among populations living in different climatic regions and provide a scientific basis for establishing appropriate indoor cooling and heating temperature standards during heat waves and cold spells.

Declarations

Declaration of competing interest

The authors confirm that they have no conflicting financial interests or personal relationships that could have influenced the findings reported in this paper.

Funding

This work was supported by Korea Planning and Evaluation Institute of Industrial Technology (KEIT) grant, funded by the Ministry of Trade, Industry & Energy (MOTIE, Korea) (20014904, RS-2024-00507617).

Author contributions

Sang-Hyun Roh: Methodology, Formal analysis, Investigation, Writing – Original Draft, Writing - Review & Editing, **Syifa Salsabila**: Methodology, Investigation, Writing - Review & Editing, **Titis Wijayanto**: Methodology, Investigation, Review & Editing, **Joo-Young Lee**: Conceptualization, Methodology, Resources, Writing - Review & Editing, Supervision, Project administration, Funding acquisition.

Acknowledgements

We thank Yoon-Jeong Hur and Hoyeon Jeong for their technical supports.

Data availability

The data included as supplemental material.

References

1. Andersen KL, Hart J, Hammel H, Sabean H (1963) Metabolic and thermal response of Eskimos during muscular exertion in the cold. J Appl Physiol 18:613–618
2. Bae J-S, Lee J-B, Matsumoto T, Othman T, Min Y-K, Yang H-M (2006) Prolonged residence of temperate natives in the tropics produces a suppression of sweating. Pflügers Archiv 453:67–72
3. Besné I, Descombes C, Breton L (2002) Effect of age and anatomical site on density of sensory innervation in human epidermis. Arch Dermatol 138:1445–1450
4. Castellani JW, Young AJ (2016) Human physiological responses to cold exposure: Acute responses and acclimatization to prolonged exposure. Auton Neurosci 196:63–74
5. Daanen HA, Racinais S, Périard JD (2018) Heat acclimation decay and re-induction: a systematic review and meta-analysis. Sports Med 48:409–430
6. Daanen HA, Van Marken Lichtenbelt WD (2016) Human whole body cold adaptation. Temperature 3:104–118

7. Gagge AP, Stolwijk JA, Hardy JD (1967) Comfort and thermal sensations and associated physiological responses at various ambient temperatures. Environ Res 1:1–20
8. Garrett AT, Goosens NG, Rehrer NG, Patterson MJ, Cotter JD (2009) Induction and decay of short-term heat acclimation. Eur J Appl Physiol 107:659–670
9. Garrett AT, Rehrer NJ, Patterson MJ (2011) Induction and decay of short-term heat acclimation in moderately and highly trained athletes. Sports Med 41:757–771
10. IUPS (2001) Glossary of terms for thermal physiology. Jpn J Physiol 51:245–280
11. Johnson CD, Melanaphy D, Purse A, Stokesberry SA, Dickson P, Zholos AV (2009) Transient receptor potential melastatin 8 channel involvement in the regulation of vascular tone. Am J Physiol Heart Circ Physiol 296:H1868–H1877
12. Kawakami T, Ishihara M, Mihara M (2001) Distribution density of intraepidermal nerve fibers in normal human skin. J Dermatol 28:63–70
13. Ko Y, Kang J, Seol S-H, Lee J-Y (2020a) Effectiveness of skin-heating using a water-perfused suit as passive and post-exercise heat acclimation strategies. J Therm Biol 93:102703
14. Ko Y, Seol S-H, Kang J, Lee J-Y (2020b) Adaptive changes in physiological and perceptual responses during 10-day heat acclimation training using a water-perfused suit. J Physiol Anthropol 39:1–11
15. Kwon J, Cho K, Jung D, Lee J-Y (2023) Cutaneous warmth and hotness thresholds to radiation heat exposure at a distance of 10 cm from 17 body regions. J Therm Biol 115:103611
16. Lauria G, Lombardi R, Camozzi F, Devigili G (2009) Skin biopsy for the diagnosis of peripheral neuropathy. Histopathology 54:273–285
17. Lee J-B, Bae J-S, Matsumoto T, Yang H-M, Min Y-K (2009) Tropical Malaysians and temperate Koreans exhibit significant differences in sweating sensitivity in response to iontophoretically administered acetylcholine. Int J Biometeorol 53:149–157
18. Lee J-Y, Bakri I, Toramoto S, Tochihara Y (2011) Cutaneous thermal thresholds of tropical indigenes residing in Japan. J Therm Biol 36:461–468
19. Lee J-Y, Saat M, Chou C, Hashiguchi N, Wijayanto T, Wakabayashi H, Tochihara Y (2010) Cutaneous warm and cool sensation thresholds and the inter-threshold zone in Malaysian and Japanese males. J Therm Biol 35:70–76
20. Lee J (2005) A study on the body surface area of Korean adults. Ph. D. Dissertation of Seoul National University
21. Leppaluoto J, Korhonen I, Hassi J (2001) Habituation of thermal sensations, skin temperatures, and norepinephrine in men exposed to cold air. J Appl Physiol 90:1211–1218
22. Lin TP, De Dear R, Hwang RL (2011) Effect of thermal adaptation on seasonal outdoor thermal comfort. Int J Climatol 31:302–312
23. Liu H, Wu Y, Li B, Cheng Y, Yao R (2017) Seasonal variation of thermal sensations in residential buildings in the Hot Summer and Cold Winter zone of China. Energy Build 140:9–18
24. Lorenzo S, Halliwill JR, Sawka MN, Minson CT (2010) Heat acclimation improves exercise performance. J Appl Physiol 109:1140–1147
25. Matsumoto T, Kosaka M, Yamauchi M, Tsuchiya K, Ohwatari N, Motomura M, Otomasu K, Yang G-J, Lee J-M, Boonayathap U (1993) Study on mechanisms of heat acclimatization due to thermal sweating: comparison of heat-tolerance between Japanese and Thai subjects. Trop Med 35:23–34
26. McArthur JC, Stocks EA, Hauer P, Cornblath DR, Griffin JW (1998) Epidermal nerve fiber density: normative reference range and diagnostic efficiency. Arch Neurol 55:1513–1520
27. Nakamura Y, Okamura K (1998) Seasonal variation of sweating responses under identical heat stress. Appl Human Sci 17:167–172
28. Oseland N (1994) A comparison of the predicted and reported thermal sensation vote in homes during winter and summer. Energy Build 21:45–54
29. Pandolf K (1998) Time course of heat acclimation and its decay. Int J Sports Med 19:S157–S160
30. Reilly D, Ferdinando D, Johnston C, Shaw C, Buchanan K, Green M (1997) The epidermal nerve fibre network: characterization of nerve fibres in human skin by confocal microscopy and assessment of racial variations. Br J Dermatol 137:163–170
31. Saat M, Tochihara Y, Hashiguchi N, Sirisinghe RG, Fujita M, Chou CM (2005) Effects of exercise in the heat on thermoregulation of Japanese and Malaysian males. J Physiol Anthropol Appl Hum Sci 24:267–275
32. Schlader ZJ, Simmons SE, Stannard SR, Mündel T (2011) The independent roles of temperature and thermal perception in the control of human thermoregulatory behavior. Physiol Behav 103:217–224

33. Sheffield D, Biles PL, Orom H, Maixner W, Sheps DS (2000) Race and sex differences in cutaneous pain perception. Psychosom Med 62:517–523
34. Shvartz E, Bhattacharya A, Sperinde S, Brock P, Sciaraffa D, Van Beaumont W (1979) Sweating responses during heat acclimation and moderate conditioning. J Appl Physiol 46:675–680
35. Umemiya N (2006) Seasonal variations of physiological characteristics and thermal sensation under identical thermal conditions. J Physiol Anthropol 25:29–39
36. Wakabayashi H, Wijayanto T, Lee J-Y, Hashiguchi N, Saat M, Tochihara Y (2011) Comparison of heat dissipation response between Malaysian and Japanese males during exercise in humid heat stress. Int J Biometeorol 55:509–517
37. Watson PJ, Latif RK, Rowbotham DJ (2005) Ethnic differences in thermal pain responses: a comparison of South Asian and White British healthy males. Pain 118:194–200

Figures

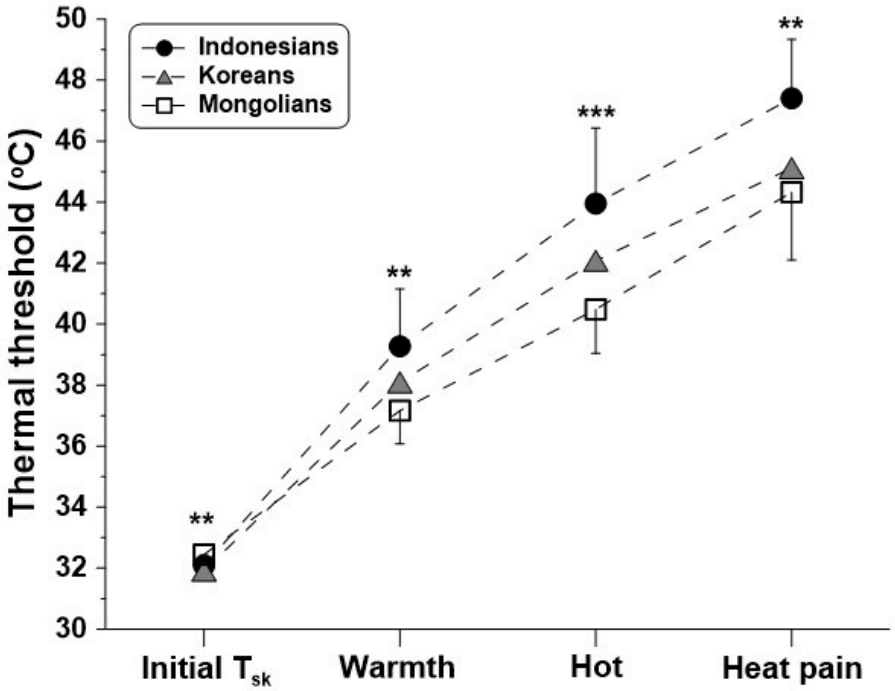


Figure 1. Initial mean skin temperature ($\bar{T}_{sk}$) and thermal thresholds (warmth, hot, and heat pain) for the whole body of Indonesian, Korean, and Mongolian males during contact heat stimulation. $^{**}P<0.01$ and $^{***}P<0.001$ indicate significant differences among the three groups. The whole-body thermal threshold was calculated as the surface area–weighted average of the thermal thresholds measured across 17 body regions.

Figure 1

See image above for figure legend

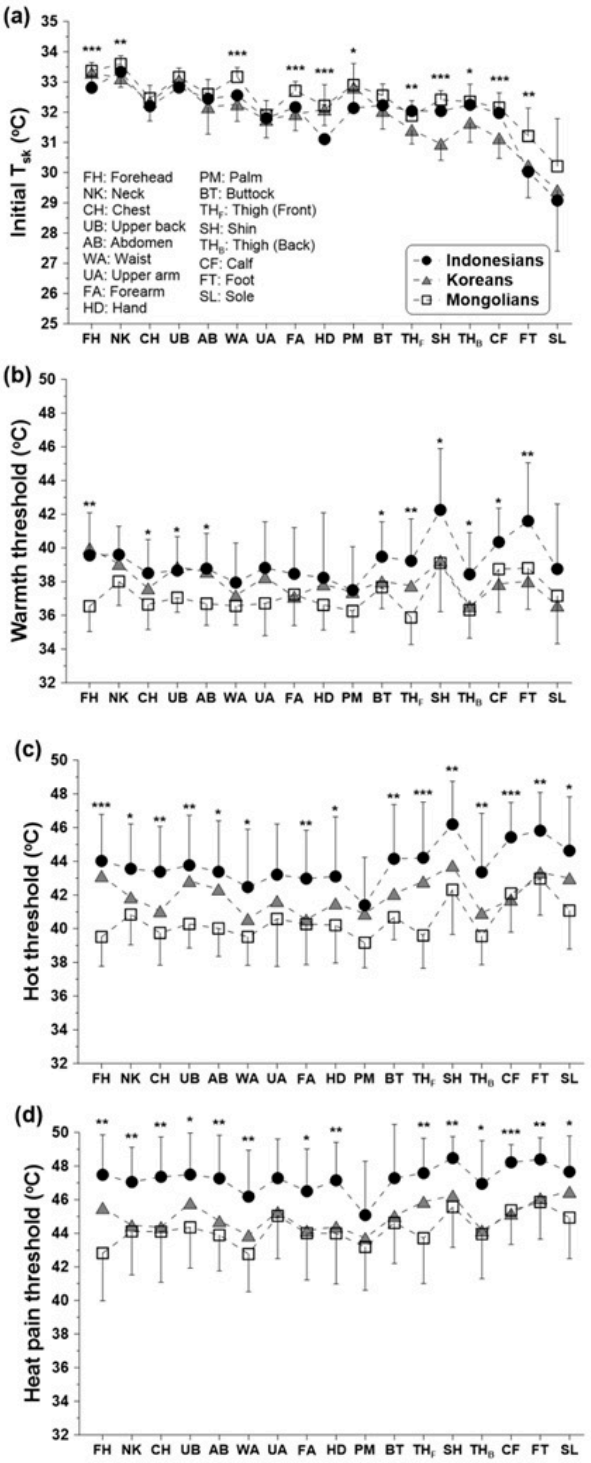


Figure 2

Regional initial T_{sk} (a) and cutaneous warmth (b), hot (c), and heat pain (d) thresholds of Indonesians, Koreans, and Mongolians during contact heat stimulation. $^{*}P<0.05$, $^{**}P<0.01$, and $^{***}P<0.001$ indicate significant differences among the three groups.

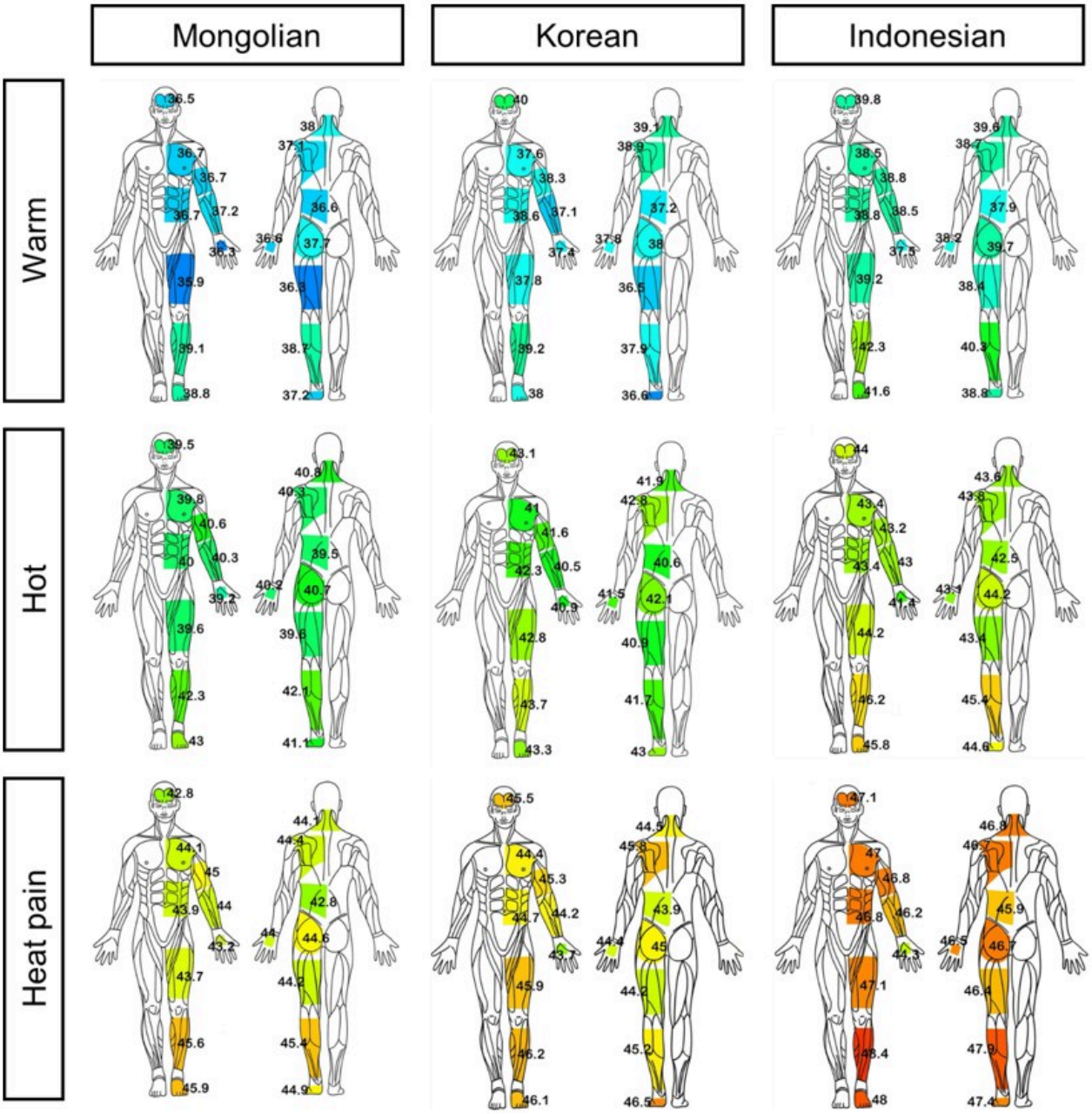


Figure 3

Thermal body mapping of regional thermal thresholds (warmth, hot, and heat pain) in Mongolians, Koreans, and Indonesians during contact heat. The numbers in each body region indicate the mean values

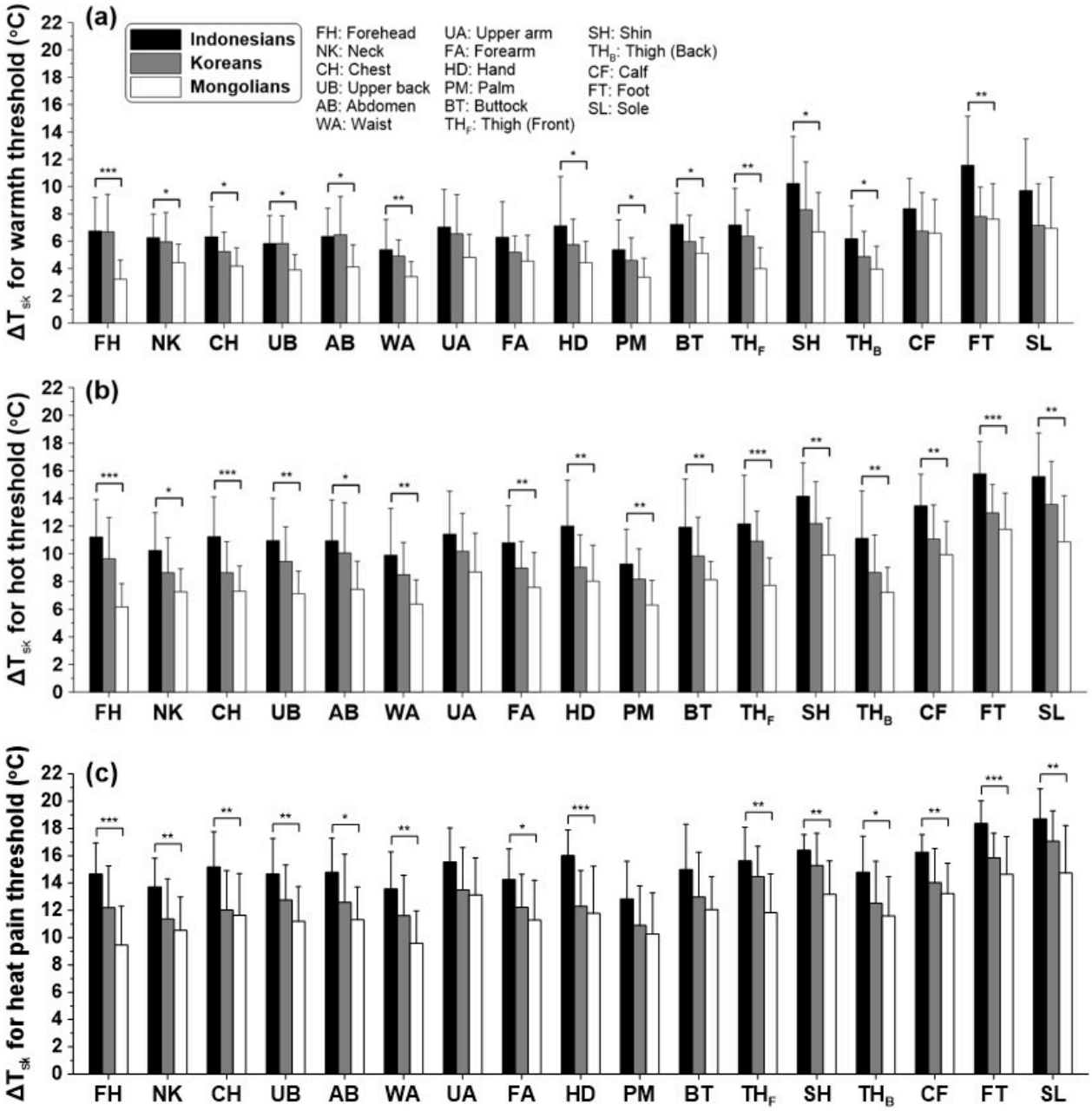


Figure 4

Regional temperature increment (ΔT_{sk}) from the initial T_{sk} to cutaneous warmth (a), hot (b), and heat pain (c) thresholds of Indonesians, Koreans, and Mongolians during contact heat. $^{*}P<0.05$, $^{**}P<0.01$, and $^{***}P<0.001$ indicate significant differences among the three groups.

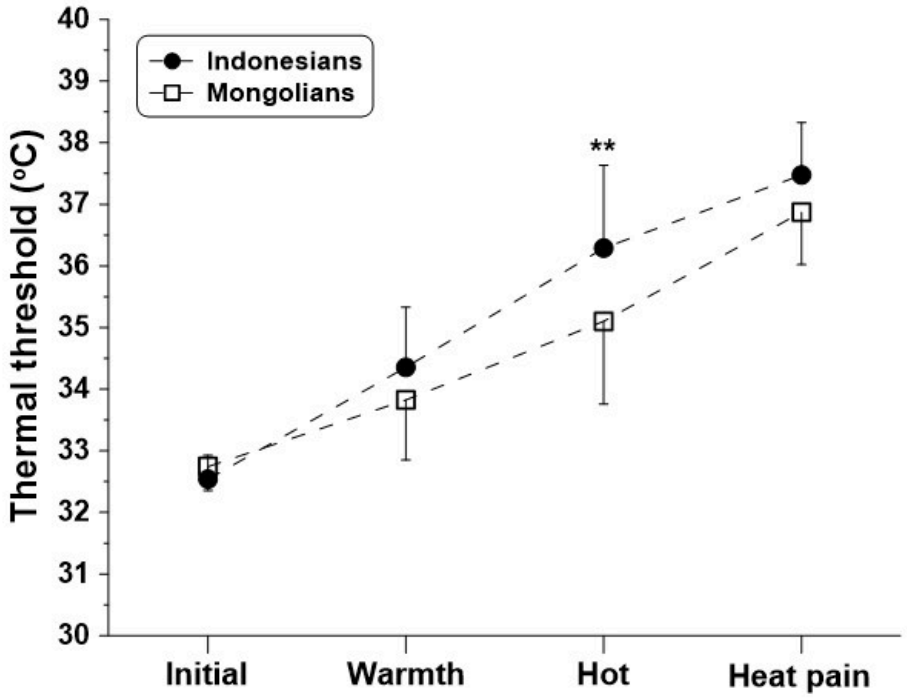


Figure 5

Initial skin temperature (T_{sk}) and thermal thresholds (warmth, hot, and heat pain) for all Indonesian and Mongolian males during radiant heat stimulation. $^{**}P<0.01$ indicate significant differences between the two groups. The whole-body thermal threshold was calculated as the surface area–weighted average of the thermal thresholds measured across 17 body regions.

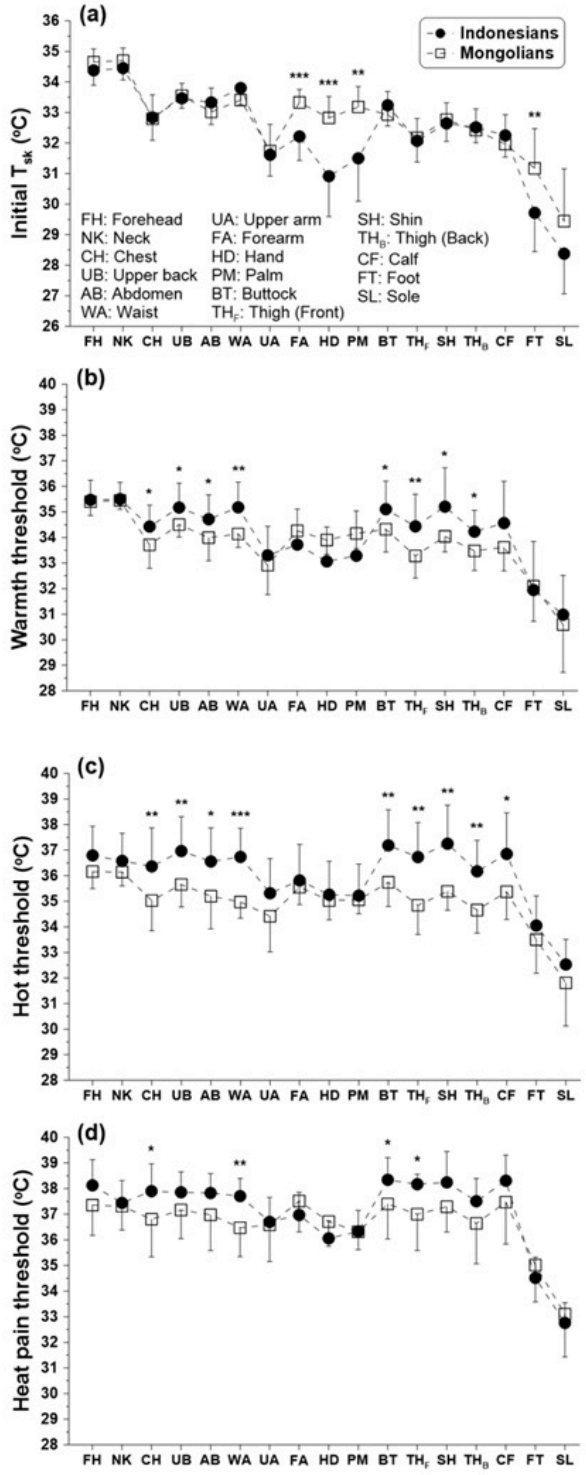


Figure 6

Regional initial T_{sk} (a) and cutaneous warm (a), hot (b), and heat pain (c) thresholds of Indonesians and Mongolians from radiant heat. $^{*}P<0.05$, $^{**}P<0.01$, and $^{***}P<0.001$ indicate significant differences among the three groups.

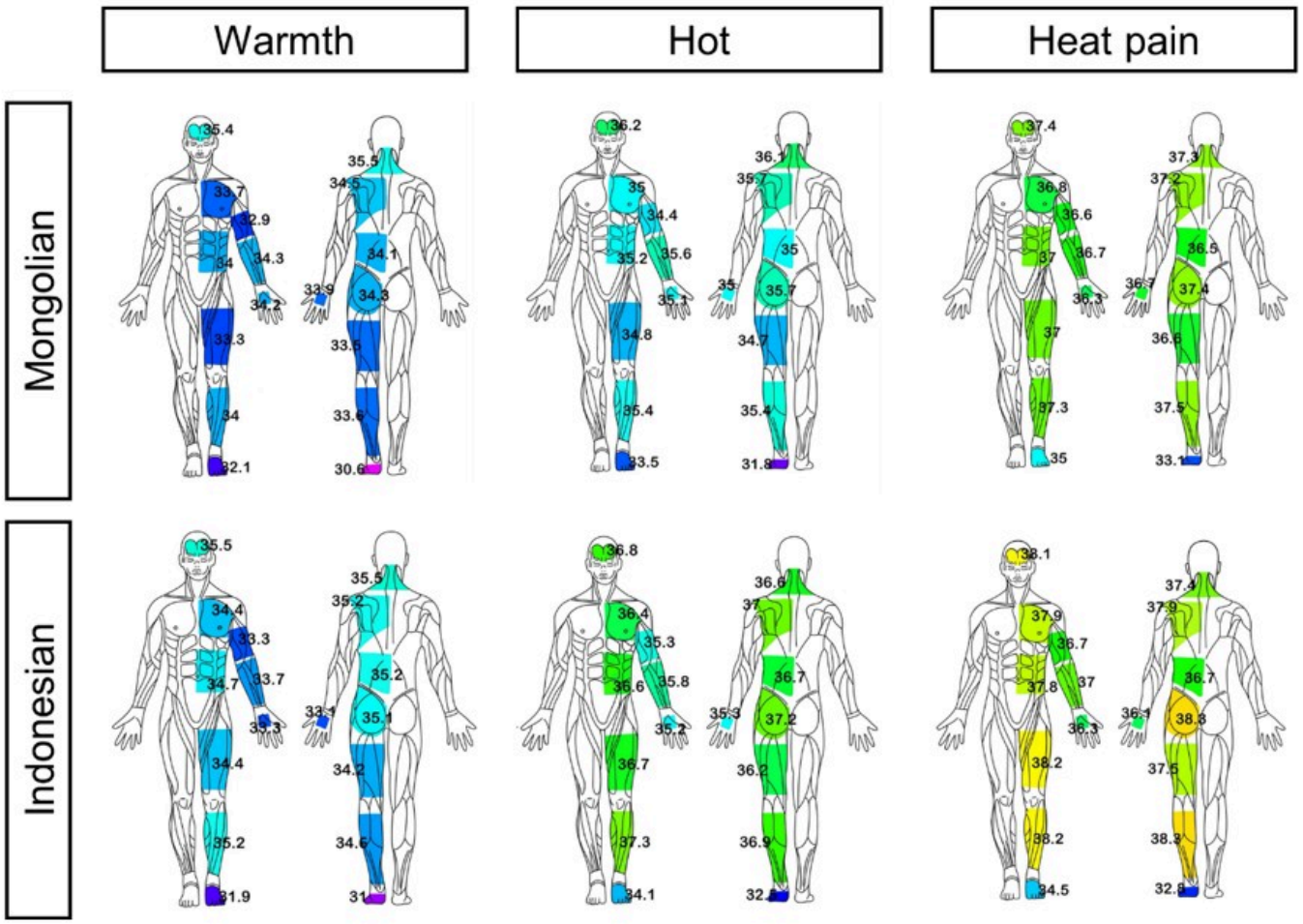


Figure 7

Thermal body mapping of regional thermal thresholds (warmth, hot, and heat pain) for Mongolians and Indonesians from radiant heat.

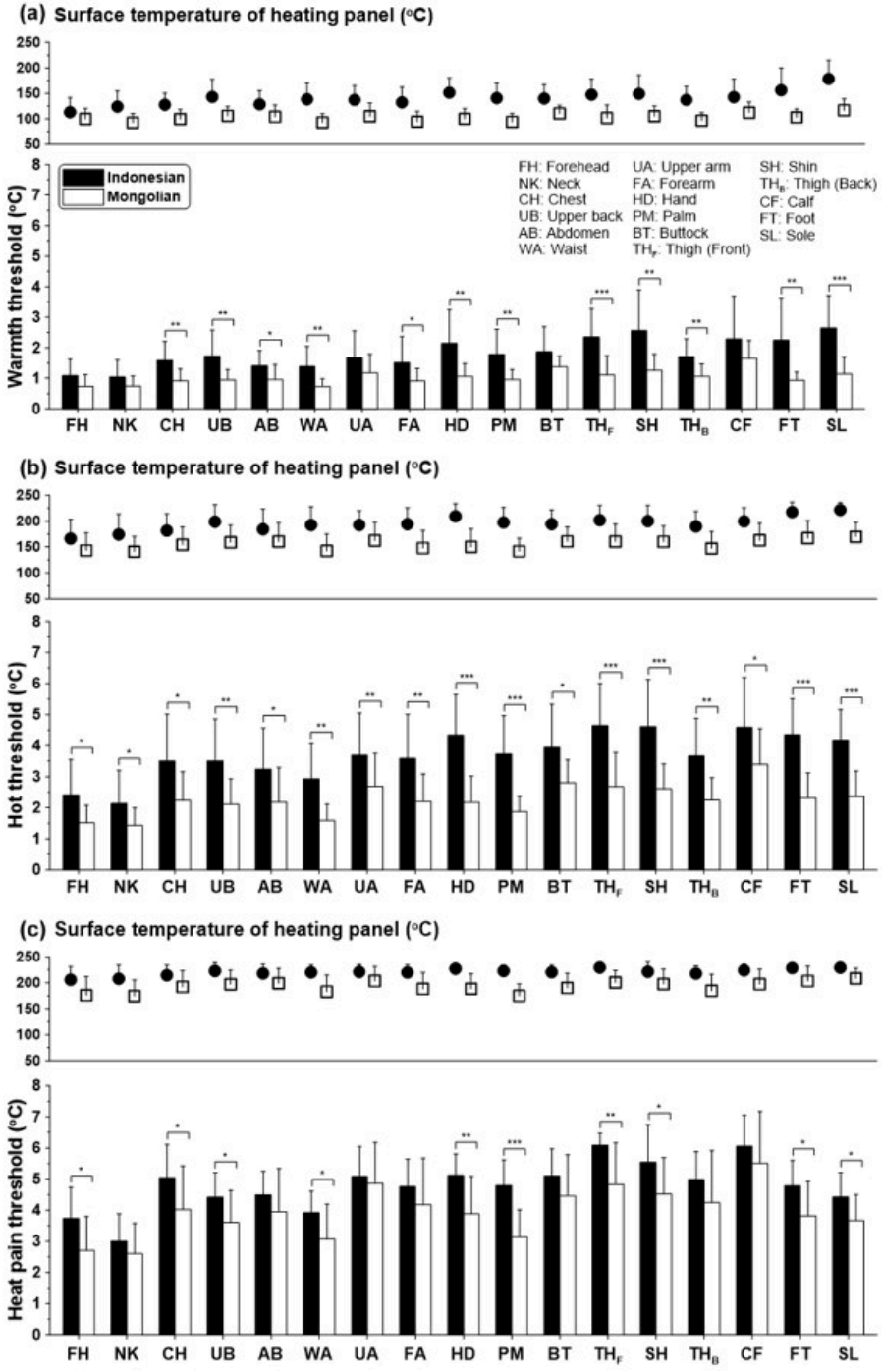


Figure 8

Surface temperature of heating panel and regional temperature increment (ΔT_{sk}) from the initial T_{sk} to cutaneous warmth (a), hot (b), and heat pain (c) thresholds of Indonesians and Mongolians during radiant heat. $^{*}P<0.05$, $^{**}P<0.01$, $^{***}P<0.001$.