

The effects of firefighting boots and personal protective equipment load on foot thermal comfort

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Abstract

Maintaining foot comfort is important as it influences the overall comfort of the human body. Shoe microclimate and foot skin temperature have been suggested to contribute to the thermal sensation of the foot. Considering the thermal environment and personal protective equipment (PPE) used for structural and proximity firefighting, climatic chamber tests with 13 male participants were conducted during standing and walking. Four test conditions – unloaded with training shoes, loaded with training shoes, unloaded with firefighting boots, and loaded with firefighting boots – were designed to investigate the effects of firefighting boots and PPE load on the thermal comfort of the human foot. Physiological variables of in-shoe and foot skin temperature at the whole and local regions of the foot were measured and subjective responses were gathered using psychological scales. The results showed that wearing firefighting boots may elevate the thermal sensation of wearers. The PPE load increased the in-shoe and foot skin temperature as well as subjective ratings. Subjective sensations of the foot were strongly correlated with in-shoe and skin temperature in the plantar regions. Correlation analysis of thermal sensation at the whole and local foot regions indicated that the sensation at the forefoot was closest to the whole foot, followed by the midfoot and heel. The findings address the relationship of physiological and subjective variables as well as the thermal sensation of whole and local foot regions, which can be considered for footwear design and thermal comfort prediction of the foot and whole body.

Keywords

Thermal environment, foot, thermal sensation, firefighting boots, personal protective equipment

When the whole body sensation is perceived as thermally neutral, the foot sensation is cooler.¹ The foot generally has a lower local skin temperature than the head or hands, as Ciuha and Mekjavic reported.² Although the foot only accounts for 7% of the body surface area, it is a significant thermal radiator for human thermoregulation.^{3,4} Therefore, it is important to maintain foot comfort as it has a great impact on the overall comfort of the human body.⁵

Evaluating thermal comfort is quite a difficult task since the individual perception of comfort is affected by a variety of factors.^{6,7} Shoe microclimate, including in-shoe temperature and humidity, has been suggested to contribute to the perceived sensation of foot thermal comfort.⁸ The inside footwear temperature has a greater influence on thermal sensation than humidity.^{9,10} Research indicates that foot skin temperature varies

from 25°C to 40°C.¹¹ A temperature beyond the comfortable range (exceeding 34°C) results in the perception of thermal discomfort,¹² and the thermoregulatory mechanisms of sweating for the human body are triggered when the upper threshold of foot skin temperature is exceeded.¹³ Wear trials and a five-point rating scale are used to obtain subjective data on foot thermal comfort.⁵

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A variety of studies have been conducted to investigate the effects of running shoes,⁸ trekking boots,⁷ and ski boots¹⁴ on foot thermal comfort in moderate and cold environments, respectively. The skin surface temperature and subjective perceptions were recorded in the whole and local regions of the foot before and after the physical task. Analysis of the data demonstrated that the heating of feet produced a strong local and overall comfort reaction in cold conditions.¹ There were differences between the physiological indicators and the subjective ratings of thermal comfort, and the subjective perception of thermal comfort appeared to be more related to foot temperature increase than to the moisture retention inside the footwear.

Firefighting boots provide a protective function for firefighters in hot environments.^{9,13} The steel toecaps and anti-puncture insoles that aim to achieve this function increase the rigidity and weight of the footwear, hence decreasing the biomechanical and hygienic properties.¹⁵ In addition to boots, PPE (personal protective equipment) – turnout suit, helmet, gloves, and self-contained breathing apparatus (SCBA) – adds a significant physical burden during firefighting.¹⁶ The literature indicates that performing work in excessively heavy PPE or load carriage results in higher energy expenditure and restricted human motion. These may lead to overexertion, heat stress, and muscle strain.^{17,18} To understand the effects of firefighting boots on foot thermal comfort, Irzmańska et al.^{13,19,20} investigated microclimate parameters inside footwear by measuring the foot skin temperature and the peripheral blood flow, in conjunction with user evaluation. However, the experiments were conducted under constant climatic conditions with air temperatures of $23 \pm 2^\circ\text{C}$, which cannot reflect the actual operating conditions in hot environments. Moreover, the influence mechanism of the physical burden caused by PPE on foot thermal comfort is not clear.

The purpose of this study was to investigate the effects of firefighting boots and PPE load on foot thermal comfort. Human subject wear trials were performed under simulated conditions using a treadmill ergometer. In-shoe temperature and foot skin temperature were monitored at specific foot areas and subjective ratings were obtained during and after testing. The findings of this study would be useful for designing and optimizing firefighting boots.

Method

Participants

Thirteen healthy men (age: 18–28; height: 170–185; BMI: 18.5–23.9; shoe size: 41–43) volunteered to

participate in this study. The subjects were informed of the test procedures and gave written informed consent before testing. All participants exercised as part of their daily routine and were right-foot dominant. A medical exam confirmed that the participants had not had any foot disease or injury in the past six months.

Footwear and load carriage

The training shoes worn by armed police were compared with firefighting boots. A physical training uniform and socks were considered basic wear, and the PPE, including firefighter clothing, helmet, gloves, SCBA, and a belt, was identified as the PPE load. The characteristics of the components and weight of each item are listed in Table 1 (shoe size: 42). The total weight of the PPE load was 12.45 kg. The thermal resistance and moisture vapor resistance of training shoes were 0.95 clo and $35.36 (\text{Pa}\cdot\text{m}^2)/\text{W}$ and these of firefighting boots were 0.80 clo and $169.59 (\text{Pa}\cdot\text{m}^2)/\text{W}$, respectively.

A three-dimensional (3D) foot scanner (Human Solutions, Germany) was used to obtain the geometries of the foot and footwear. The right foot in training shoes and firefighting boots of one subject with a shoe size of 42 are shown in Figure 1. The air gap between the foot and these two items of footwear is similar. The higher vamp of firefighting boots than training shoes results in a larger air gap between the foot instep and the firefighting boots. To quantify the inside space of the footwear, a sample with a shoe size of 42 was disassembled and the specific dimensions inside the footwear are shown in Table 2. The height at the arc and the width at the sole of firefighting boots are larger than those of training shoes.

Experimental design and procedure

Figure 2 presents the experimental procedure. Experiments were performed in a climate-controlled room at normal conditions of 24°C , 50% relative humidity, and elevated conditions of 32°C , 60% relative humidity to simulate firefighting operation. Participants were asked to arrive 30 min before a test for acclimatization and preparation. To investigate the effects of firefighting boots and PPE load on the thermal comfort of the human foot, four test conditions were designed (Figure 3): unloaded with training shoes (U-TS); loaded with training shoes (L-TS); unloaded with firefighting boots (U-FB); and loaded with firefighting boots (L-FB). The basic wear was provided for each participant. The loaded condition was a test conducted with the PPE load, as identified in Table 1. Participants took part in two exercise trials with different activity levels – a standing test (Part I)

Table 1. Characteristics of the items used in the tests

Categories	Items	Image	Components	Weight (kg)
Basic wear	Physical training uniform		Polyester	0.29
	Socks		Cotton, polyester, and spandex	0.04
Footwear	Training shoes		Upper: nylon and synthetic leather Sole: rubber	0.71
	Firefighting boots		All-rubber, internal steel toecaps, steel insoles	2.21
PPE load	Turnout suit		Three-layered structure of the flame-retardant outer shell, moisture barrier, and thermal liner	2.81
	Helmet		Reinforced plastic, nylon, and synthetic leather	1.06
	Gloves		Three-layered structure of the flame-retardant outer shell, moisture barrier, and thermal liner	0.16
	SCBA		A four-layered composite structure of aluminum alloy, carbon fiber, glass fiber, and epoxy resins	7.70
	Belt		Nylon, synthetic leather, and stainless steel	0.72

PPE: personal protective equipment; SCBA: self-contained breathing apparatus.



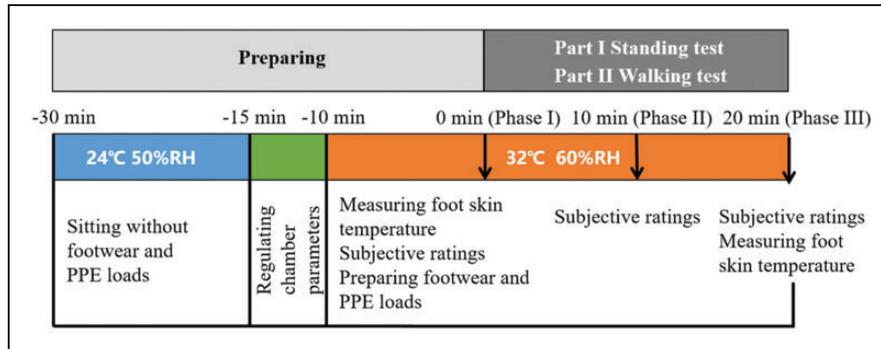
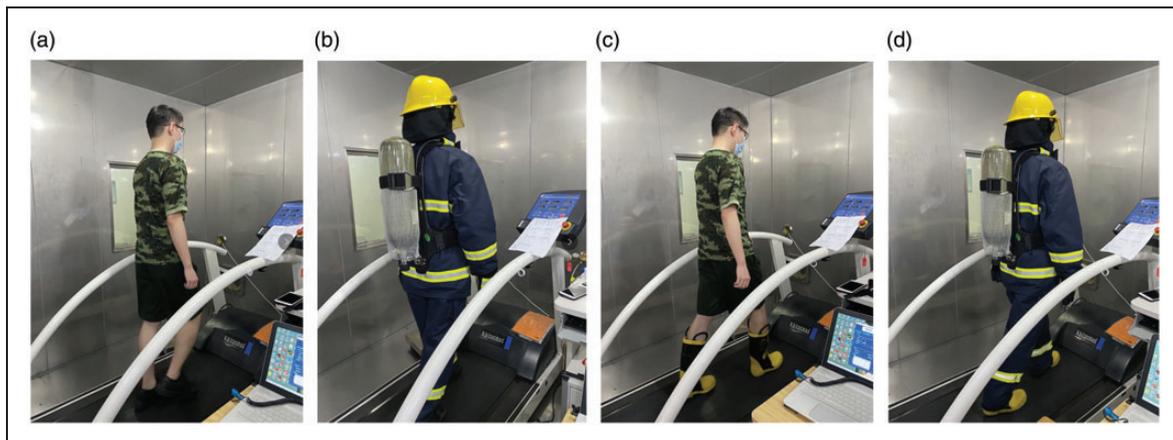
Figure 1. Three-dimensional geometries of the right foot with training shoes (a) and firefighting boots (b), and both items of footwear (right).

and a walking test on a treadmill at a constant speed of 4.5 km/h (Part II). The standing test (Part I) and walking test (Part II) were performed for 20 min under the elevated temperature condition. A total of eight

wear trials (4 test conditions \times 2 activity levels) for each subject were performed. The experimental protocol and procedure were approved by Donghua University.

Table 2. Inside space dimensions of the footwear

Dimension (cm)	Length	Width at the sole	Width at the heel	Height at the toe cap	Height at the arc
Training shoes	26.78	8.83	5.76	3.24	6.72
Firefighting boots	26.52	9.36	5.69	3.93	8.56

**Figure 2.** Experimental procedure. PPE: personal protective equipment.**Figure 3.** Wear trials with four test conditions. (a) U-TS (b) L-TS (c) U-FB (d) L-FB. U-TS: unloaded with training shoes; L-TS: loaded with training shoes; U-FB: unloaded with firefighting boots; L-FB: loaded with firefighting boots.

The in-shoe temperatures were taken at 0 min (Phase I), 10 min (Phase II), and 20 min (Phase III), and the foot skin temperatures were taken at Phase I and Phase III to analyze the temperature increase during the test. Subjective evaluations on the thermal sensation were performed at Phases I–III. For each activity level, all four test conditions of U-TS, L-TS, U-FB, and L-FB were conducted.

The subjective characteristics and objective sensations were monitored during the trials. As shown in Figure 4, three areas – the forefoot, midfoot, and heel – were divided for the plantar foot, and the in-shoe temperature was determined using iButton wireless temperature loggers (Maxim, USA). The diameter and thickness of iButton were 1.7 and 0.6 cm, respectively. The temperatures were only taken on the right-

hand dominant foot, so the sensors were embedded in the right-hand insole to record the temperature variations of the foot microclimate. Foot skin temperature was measured immediately before and after exercise by a non-contact infrared thermometer, Optris PI400 (Optris GmbH, Germany). A thermal infrared image was taken of the sole for each test. Temperatures of the plantar foot were extracted according to the sensor locations for in-shoe temperature measurement. Subjective evaluations on the thermal sensation of the participants were evaluated based on ASHRAE 55²¹ using a seven-point scale (−3: cold, −2: cool, −1: slightly cool, 0: neutral, +1: slightly warm, +2: warm, +3 hot) during the experiments. The thermal state of the whole foot and three local areas (forefoot, midfoot, and heel) of the participants was obtained for the right



Figure 4. Plantar foot regions and the position of sensors on the right foot.

foot. All subjects were instructed to use the scale and practice to familiarize themselves with the rating method before formal experiments, to receive more accurate subjective responses at the whole and local areas of the foot.

Statistical analysis

Mean values and standard deviations were calculated for the in-shoe temperature and the foot skin temperature as well as the subjective ratings for the whole foot and three plantar foot regions. A repeated-measures analysis of variance (ANOVA) test was carried out using SPSS Statistics 25.0 (SPSS Inc., USA) for the values showing the normal distribution, to determine whether there were any significant differences among test conditions at a significance level of 0.05. Pairwise comparison of mean values was performed using post-hoc tests with the least significant difference (LSD) correction for multiple comparisons. Non-parametric methods were used for variance analyses of non-normally distributed data. Correlations between the objective temperature parameters and the subjective sensations were examined for different footwear and load conditions. The correlation analysis was also conducted to determine the relation between local and whole foot subjective ratings.

Results

Part I: standing test

In-shoe temperature. The mean and standard deviation of the in-shoe temperatures for all test conditions during the standing test are presented in Figure 5.

The in-shoe temperature increased for all three plantar foot areas due to elevated air temperatures in the climatic chamber and human foot. The temperature inside the footwear in the heel area was lower than in the forefoot and midfoot regions for all footwear and under all load conditions after 5 min of standing. At the beginning of the standing test (Phase I), the temperature of the forefoot, midfoot, and heel ranged from 26.6°C to 27.8°C, 27.1°C to 28°C, and 27°C to 27.9°C, respectively. After 20 min of standing (Phase III), the temperature range increased to 30.4–31.5°C, 30.5–31.2°C, and 29–29.7°C, respectively. A smaller temperature increase was observed in the heel area.

The in-shoe temperature for U-TS was close to U-FB at the forefoot and midfoot. A remarkably lower temperature was found for U-TS than U-FB at the heel, indicating that the application of firefighting boots increased the in-shoe temperature in this area. When a PPE load was added, the in-shoe temperature of L-TS was less than L-FB during the early stage of the standing test, then the L-TS exceeded the L-FB during the latter stage of the test. A higher in-shoe temperature was detected in testing with PPE load under both footwear conditions in the three plantar areas.

The mean temperature increases from Phase I to Phase II and Phase III in the forefoot, midfoot, and heel areas are listed in Table 3. After 10 min of standing, the in-shoe temperature in the forefoot increased by an average of 2.1°C. The average temperature increases for the four test conditions at the midfoot and heel areas were 2°C and 1.6°C, respectively. The highest average temperature increase was 3.7°C at the forefoot area at the end of the experiment, followed by 3.3°C at the midfoot and 2°C at the heel.

Regarding the four test conditions, significant temperature increases were observed in all areas ($p < 0.05$), except the forefoot ($p = 0.08$). The temperature increase for L-TS was the greatest in all plantar regions. Higher temperature increases were found in the tests performed using the training shoes both with and without PPE load.

Foot skin temperature. Thermal infrared images of the right foot after the standing test for Subject 1 are shown in Figure 6. The foot sole was divided into five regions based on the temperature distribution. The condition of U-TS exhibited lower skin temperature on the foot, indicating the effects of firefighting boots and PPE load on increased foot temperature. Relatively higher foot skin temperatures were observed for L-TS. Skin temperatures of participants wearing firefighting boots were higher than those wearing training shoes unloaded, but lower than those wearing training shoes loaded. The lower temperature was detected

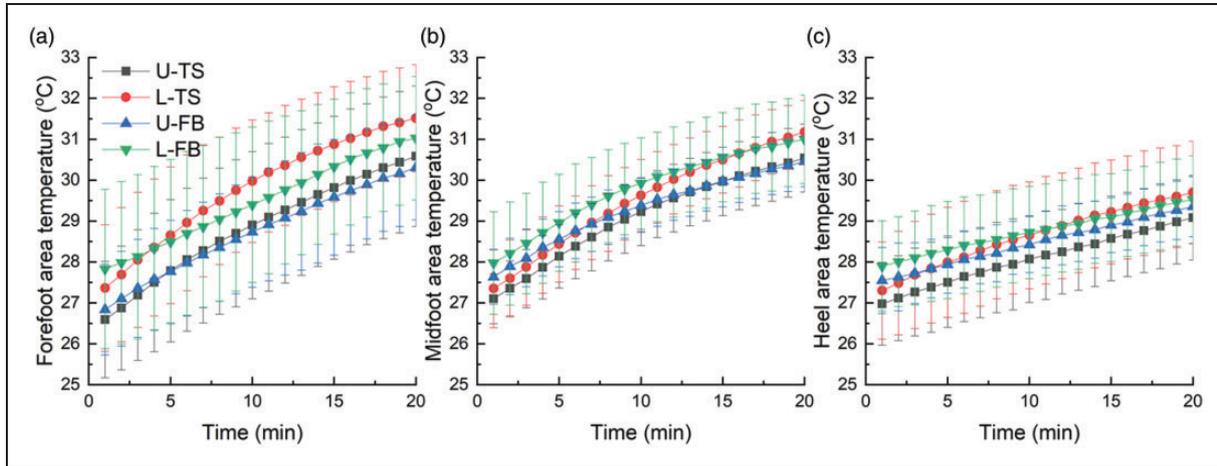


Figure 5. Mean in-shoe temperatures for four footwear and load conditions during the standing test: (a) forefoot area; (b) midfoot area; (c) heel area.

Table 3. Mean of in-shoe temperature increases during the standing test

	Forefoot area		Midfoot area		Heel area	
	$T_{md} - T_{bf}^*$	$T_{af} - T_{bf}$	$T_{md} - T_{bf}^*$	$T_{af} - T_{bf}^*$	$T_{md} - T_{bf}^*$	$T_{af} - T_{bf}^*$
U-TS	2.3	4.0	2.1	3.4	1.2	2.1
L-TS	2.6	4.2	2.3	3.8	1.4	2.4
U-FB	1.9 ^b	3.5	1.8 ^{a,b}	2.8 ^{a,b}	0.9 ^b	1.8 ^b
L-FB	1.6 ^{a,b}	3.2 ^b	1.9 ^b	3.0 ^b	0.8 ^{a,b}	1.6 ^b

T_{bf} : temperature before test (Phase I); T_{md} : temperature at the middle of test (Phase II); T_{af} : temperature after test (Phase III); U-TS: unloaded with training shoes; L-TS: loaded with training shoes; U-FB: unloaded with firefighting boots; L-FB: loaded with firefighting boots.

*Significant difference at level of 0.05; ^asignificant difference from U-TS ($p < 0.05$); ^bsignificant difference from L-TS ($p < 0.05$); ^csignificant difference from U-FB ($p < 0.05$).

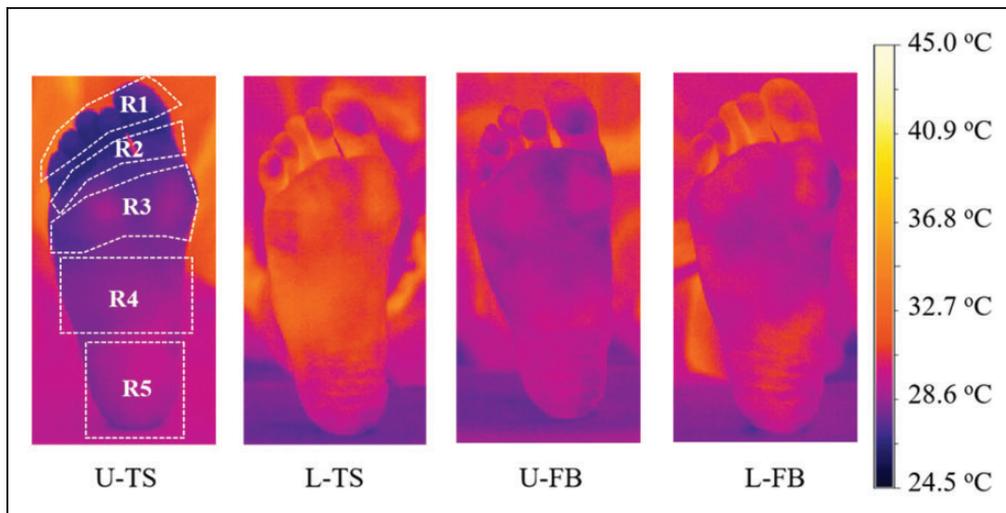


Figure 6. Thermal infrared images of the right foot after the standing test for Subject I. U-TS: unloaded with training shoes; L-TS: loaded with training shoes; U-FB: unloaded with firefighting boots; L-FB: loaded with firefighting boots.

Table 4. Mean of foot skin temperature and temperature increase during the standing test

	Forefoot area			Midfoot area			Heel area		
	T_{bf}	T_{af}	$T_{af} - T_{bf}^*$	T_{bf}	T_{af}	$T_{af} - T_{bf}^*$	T_{bf}	T_{af}	$T_{af} - T_{bf}$
U-TS	29.7	32.7	3.0	33.1	33.6	0.5	31.0	33.6	2.6
L-TS	29.1	34.2	5.1 ^a	32.7	34.5	1.8 ^a	30.4	34.3	3.8
U-FB	29.0	32.6	3.6	32.6	33.4	0.8 ^b	31.0	33.4	2.4
L-FB	28.4	34.1	5.8 ^{a,c}	32.4	34.2	1.8 ^{a,c}	30.4	33.2	2.8

T_{bf} : temperature before test (Phase I); T_{af} : temperature after test (Phase III); U-TS: unloaded with training shoes; L-TS: loaded with training shoes; U-FB: unloaded with firefighting boots; L-FB: loaded with firefighting boots.

*Significant difference at level of 0.05; ^asignificant difference from U-TS ($p < 0.05$); ^bsignificant difference from L-TS ($p < 0.05$); ^csignificant difference from U-FB ($p < 0.05$).

at the toes (R1) and the neck of the toes (R2) for U-TS. Wearing firefighting boots and carrying a PPE load elevated foot skin temperatures, especially in these two regions. Carrying the PPE load increased the foot skin temperatures at the arch (R4) with training shoes, and increased the temperatures at R1, R2, and R5 with firefighting boots. The temperature distribution was not significantly different, but higher temperatures were found at the toes (R1), the neck of the toes (R2), and plantar heel (R5) with the PPE load.

Skin temperatures at the three areas of the forefoot, midfoot, and plantar heel foot were extracted from the thermal infrared images. The average temperature increases during the standing test and the mean foot skin temperature for all 13 subjects are presented in Table 4. During the 20 min standing test, the temperature at the forefoot increased by 3.0–5.8°C, and those at the heel and midfoot increased by 2.4–3.8°C and 0.5–1.8°C, respectively. The average temperature increase rate was 15.1% at the forefoot, followed by 9.5% at the heel and 3.7% at the midfoot. The temperature at the forefoot exhibited the greatest increase of 20.3% in the L-FB test, and the smallest increase of 1.4% at the midfoot in the U-TS test.

The temperature increases in the four conditions proved to be statistically significant in the forefoot ($p = 0.028$) and midfoot areas ($p = 0.014$). No significant difference was found in the heel area ($p = 0.377$). Higher temperature increases in all foot areas were observed when tests were conducted with a PPE load. Differences at the forefoot and midfoot were significant ($p < 0.05$). No footwear-related difference was found at the plantar areas of the foot.

Perceptual responses. The perceptual responses of the whole foot and local foot areas were analyzed by box charts. The subjective ratings of the 13 participants were fairly consistent. Taking no account of the outliers, the mean and standard deviation subjective ratings were calculated and are presented in Figure 7. The variations of perceptual responses were similar for the

whole and local foot areas. An increase in perceived temperature was noted in the subjective ratings during the 20 min standing test. The thermal sensations started at slightly cool and neutral in Phase I and were elevated to slightly warm at the end of the standing test (Phase III). A rapid increase of perceptual response was observed from Phase I to Phase II, and the increase rate was reduced from Phase II to Phase III. Compared with the average values of the whole foot (Phase II: 0.86; Phase III: 1.18), the average subjective ratings at the forefoot were higher (Phase II: 0.94; Phase III: 1.21). Those values at the midfoot were lower (Phase II: 0.77; Phase III: 1.05). The average thermal sensation at the heel was the lowest (Phase II: 0.64; Phase III: 0.76).

The thermal sensations of tests with a PPE load were generally warmer than those with no load for the whole and local foot. However, the influence regulation of footwear on subjective thermal perception was not apparent, which was following the in-shoe and skin temperature records. The subjective ratings of wearing the firefighting boots with a PPE load were the highest at the end of tests in all areas. All values were higher with a PPE load than without a load, except in the forefoot with training shoes. Subjective ratings on the firefighting boots indicated a higher increase than those for the training shoes for both the whole and local areas of the foot.

Part II: walking test

In-shoe temperature. The mean and standard deviation for the in-shoe temperature for all four test conditions during the walking test are presented in Figure 8. During the 20 min walking test, the temperature trends in different regions were different from the standing test. The in-shoe temperature at the heel was the highest and lowest at the midfoot, revealing the influences of physical activity on plantar microclimate temperature distribution. At the beginning of the test (Phase I), the temperature of the forefoot, midfoot, and heel ranged from 26.8°C to 27.6°C, 27.3°C to 27.8°C,

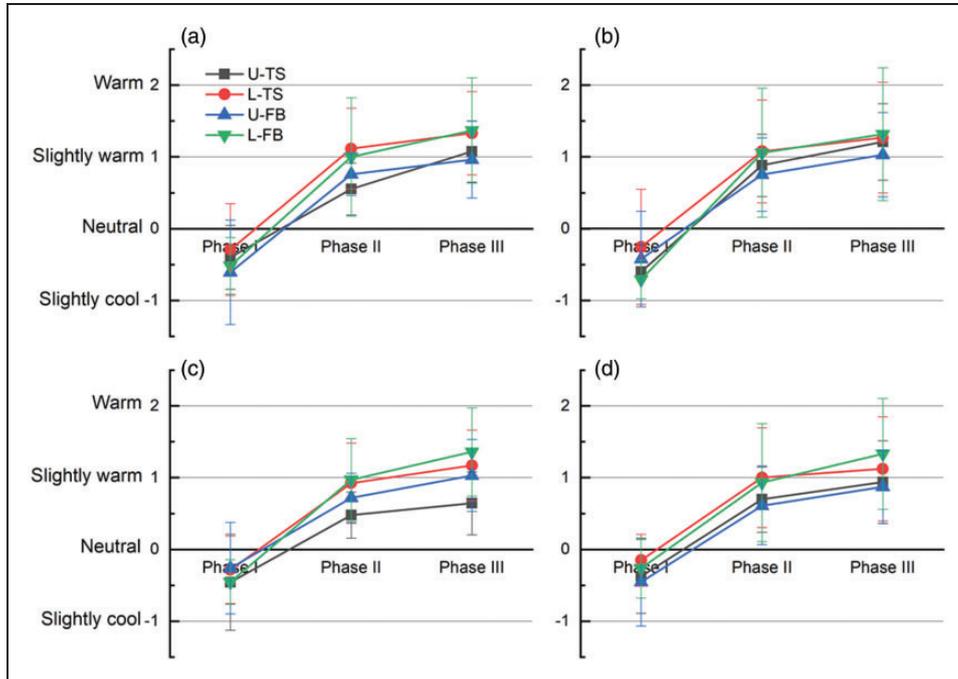


Figure 7. Average subjective ratings during the standing test: (a) whole foot; (b) forefoot area; (c) midfoot area; (d) heel area. U-TS: unloaded with training shoes; L-TS: loaded with training shoes; U-FB: unloaded with firefighting boots; L-FB: loaded with firefighting boots.

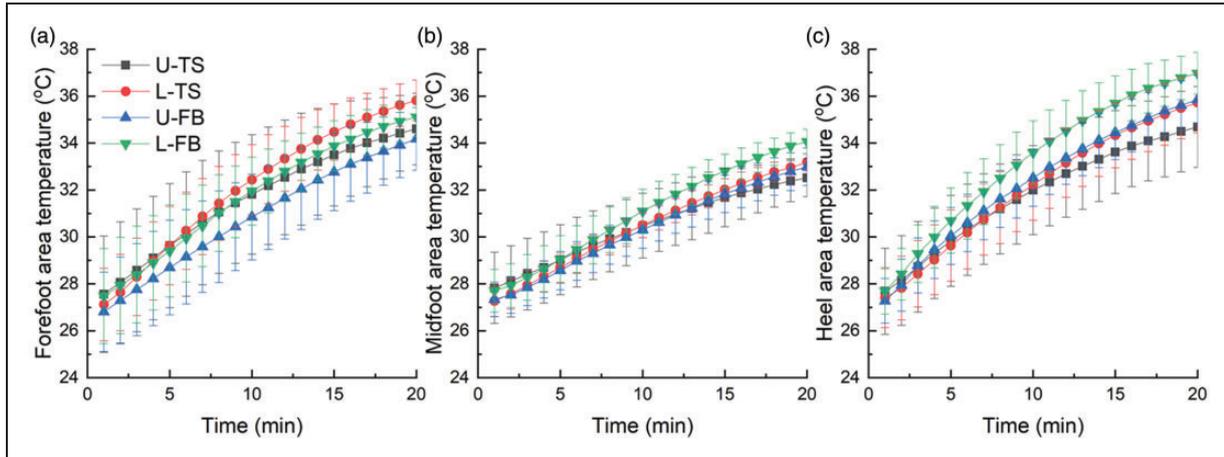


Figure 8. Mean in-shoe temperature for four footwear and load conditions during the walking test: (a) forefoot area; (b) midfoot area; (c) heel area. U-TS: unloaded with training shoes; L-TS: loaded with training shoes; U-FB: unloaded with firefighting boots; L-FB: loaded with firefighting boots.

and 27.3°C to 27.7°C, respectively. After a 20 min walking test (Phase III), temperatures reached up to 34.2–35.8°C, 32.5–34°C, and 34.7–37°C, respectively.

Carrying a PPE load increased the temperatures inside the shoes/boots, and the differences between the loaded and unloaded in-shoe temperatures increased with time. A higher in-shoe temperature was observed in the forefoot region in tests with the

training shoes, while the temperature in the midfoot and heel regions in tests with training shoes was lower than that of firefighting boots.

The mean temperature increases from Phase I to Phase II and Phase III at the forefoot, midfoot, and heel areas are listed in Table 5. After 10 min of the walking test, an average temperature elevation from Phase I of 4.5°C, 3.1°C, and 5.1°C was observed in

Table 5. Mean of in-shoe temperature increase during the walking test

	Forefoot area		Midfoot area		Heel area	
	$T_{md} - T_{bf}^*$	$T_{af} - T_{bf}$	$T_{md} - T_{bf}^*$	$T_{af} - T_{bf}^*$	$T_{md} - T_{bf}^*$	$T_{af} - T_{bf}^*$
U-TS	4.3	7.0	2.6	4.7	4.3	7.0
L-TS	5.3 ^a	8.7 ^a	3.2 ^a	5.9 ^a	4.8	8.3 ^a
U-FB	4.0 ^b	7.4 ^b	3.0 ^a	5.6 ^a	5.2 ^a	8.6 ^a
L-FB	4.5 ^b	7.6	3.4 ^{a,c}	6.4 ^{a,c}	5.9 ^{a,b}	9.3 ^a

T_{bf} : temperature before test (Phase I); T_{md} : temperature at the middle of test (Phase II); T_{af} : temperature after test (Phase III); U-TS: unloaded with training shoes; L-TS: loaded with training shoes; U-FB: unloaded with firefighting boots; L-FB: loaded with firefighting boots.

*Significant difference at level of 0.05; ^asignificant difference from U-TS ($p < 0.05$); ^bsignificant difference from L-TS ($p < 0.05$); ^csignificant difference from U-FB ($p < 0.05$).

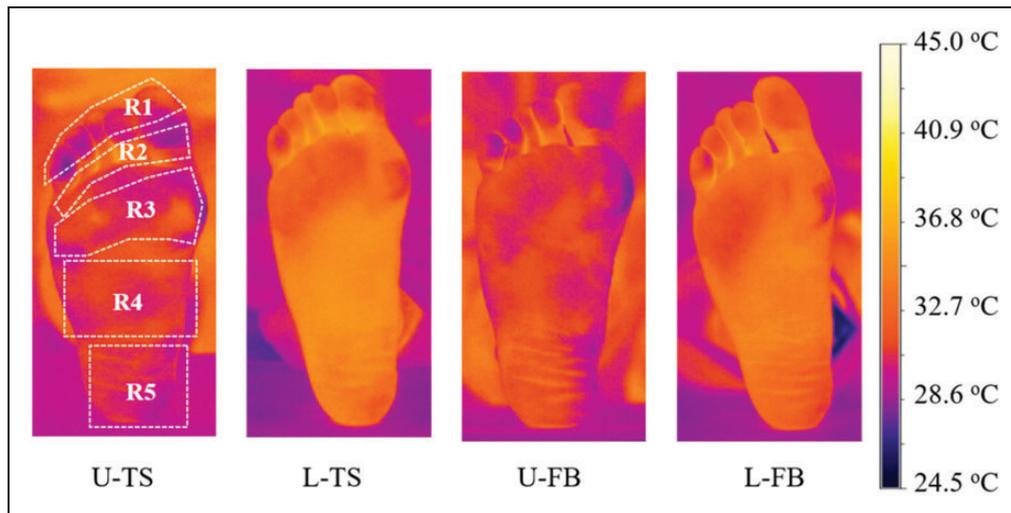


Figure 9. Thermal infrared images of the right foot after the walking test for Subject 1. U-TS: unloaded with training shoes; L-TS: loaded with training shoes; U-FB: unloaded with firefighting boots; L-FB: loaded with firefighting boots.

the forefoot, midfoot, and heel areas, respectively. At Phase III, the greatest average temperature rise of 8.3°C was found at the heel, followed by a 7.7°C increase in the forefoot and a 5.7°C increase at the midfoot.

Statistical analysis results showed that there were significant differences between temperature increase measured during tests in all areas ($p < 0.05$), except the $T_{af} - T_{bf}$ in the forefoot ($p = 0.08$). Larger temperature increases were noted in tests using a PPE load. Higher temperature increases were noted for firefighting boots when compared to training shoes, particularly in the midfoot and heel areas.

Foot skin temperature. Figure 9 displays the right-foot thermal infrared images for Subject 1 after the walking test. A remarkably higher temperature distribution was observed after the walking test when compared to those after standing tests for all conditions. Generally, the foot skin temperature was higher in tests with a PPE

load when compared to the same tests conducted without a PPE load (L-TS > U-TS; L-FB > U-FB). The effects of wearing firefighting boots were not significant. Temperature distributions of the test conditions with a PPE load (L-TS, L-FB) were more uniform than the conditions without a PPE load (U-TS, U-FB). As for local foot skin temperature, the ball (R3) of the foot showed lower temperatures, and higher temperatures were found at the neck of the toes (R2) in all foot regions regardless of test conditions. In tests without a PPE load, the toes (R1) exhibited lower skin temperatures. Higher temperatures were observed at the arch (R4) and plantar heel (R5) in tests using a PPE load (L-TS, L-FB) versus those with no PPE load (U-TS, U-FB).

Average temperature increases during the walking test were calculated in addition to the mean foot skin temperature, which are presented in Table 6. During the 20 min walking test, the temperatures at the

Table 6. Mean of foot skin temperature increases during the walking test

	Forefoot area			Midfoot area			Heel area		
	T_{bf}	T_{af}	$T_{af} - T_{bf}$	T_{bf}	T_{af}	$T_{af} - T_{bf}$	T_{bf}	T_{af}	$T_{af} - T_{bf}$
U-TS	29.0	34.3	5.3	32.6	35.5	3.0	30.8	35.1	4.2
L-TS	28.1	35.5	7.3	31.8	36.3	4.5 ^a	30.0	35.9	5.9
U-FB	28.6	34.6	6.0	32.7	35.6	2.9 ^b	30.5	35.3	4.8
L-FB	28.2	35.5	7.3	32.5	36.4	3.8	30.2	35.9	5.7

T_{bf} : temperature before test (Phase I); T_{af} : temperature after test (Phase III); U-TS: unloaded with training shoes; L-TS: loaded with training shoes; U-FB: unloaded with firefighting boots; L-FB: loaded with firefighting boots.

^aSignificant difference from U-TS ($p < 0.05$); ^bsignificant difference from L-TS ($p < 0.05$).

forefoot increased by 5.3–7.3°C, and those at the heel and midfoot increased by 4.2–5.9°C and 2.9–4.5°C, respectively. The average temperature increase rate was 22.8% at the forefoot, followed by 17% at the heel and 10.9% at the midfoot, which were higher than the standing test. The temperature at the forefoot exhibited the highest increase 26.1% in the L-TS test, and the smallest increase of 8.7% was observed in the midfoot in the U-FB test.

There were no footwear or load-related differences in the temperature increase at the heel ($p = 0.2$), which was consistent with the findings in the standing test. No significant difference was observed at the forefoot ($p = 0.25$) during the walking test. Despite no significant differences in temperature increases being found at the midfoot ($p = 0.075$), the results of posthoc tests indicated a significantly larger temperature increase in the L-TS test than in the U-TS test ($p = 0.033$) and U-FB test ($p = 0.023$). Higher temperature differences were detected for loaded conditions (L-TS, L-FB) in all locations for both footwear conditions (U-TS, U-FB). As for footwear impacts, higher temperature increases at the forefoot were found in the firefighting boots than training shoes (U-FB > U-TS; L-FB > L-TS). However, the values in the midfoot region were lower in the tests conducted using firefighting boots rather than training shoes (U-FB < U-TS; L-FB < L-TS).

Perceptual responses. The perceptual responses of the whole foot and local foot areas were analyzed by box charts. The mean and standard deviation subjective ratings were calculated by removing the outliers and are presented in Figure 10. Generally, there was an increase in the subjective ratings observed during the 20 min walking test. The thermal sensations started from the middle of slightly cool and neutral at Phase I, elevated to slightly warm at 10 min (Phase II), and reached up to warm at the end of the test (Phase III). The variations of perceptual responses were similar for the whole and local foot areas. The amplitude of rising

from Phase I to Phase II was larger than that from Phase II to Phase III. Compared with the average ratings of the whole foot (Phase II: 1.30; Phase III: 1.72), lower average subjective ratings were observed in the forefoot (Phase II: 1.22; Phase III: 1.71), midfoot (Phase II: 1.13; Phase III: 1.57), and heel (Phase II: 1.23; Phase III: 1.39). The thermal sensation in the forefoot after the 20 min walking test was close to that of the whole foot. The thermal sensations of tests with a PPE load were generally warmer than those with no load for both the whole and local foot (L-TS > U-TS; L-FB > U-FB). Higher subjective ratings were observed in testing using firefighting boots rather than training shoes with and without a PPE load (U-FB > U-TS; L-FB > L-TS), which differed from the ratings noted in the standing tests. The subjective ratings of wearing the firefighting boots with a PPE load were the highest at Phases II and III for all areas. The ascent of the ratings in the L-FB tests were the largest in the whole (2.80) and in local foot areas (forefoot: 2.64, midfoot: 2.35, heel: 2.49).

Relationship analysis

Relationship between subjective ratings and in-shoe temperatures. Regardless of the footwear/load conditions and foot areas, there was a statistically significant and positive correlation between mean subjective ratings and mean in-shoe temperatures in the standing test ($R^2 = 0.766$, $p < 0.001$) and walking test ($R^2 = 0.814$, $p < 0.001$). Figure 11 illustrates the fitting curves for these two factors by foot areas. For the standing test, the thermal sensation scores and in-shoe temperatures were highly correlated in all three local foot areas. The slope of the fitting curve at the heel (0.642) was larger than at the forefoot and at the midfoot (0.440), revealing that the thermal responses at the heel were more sensitive in the standing test. When the subjective rating was the same, the in-shoe temperature at the heel was the lowest. Concerning the walking test, foot perceptual responses and in-shoe temperatures were highly correlated in the forefoot and midfoot regions.

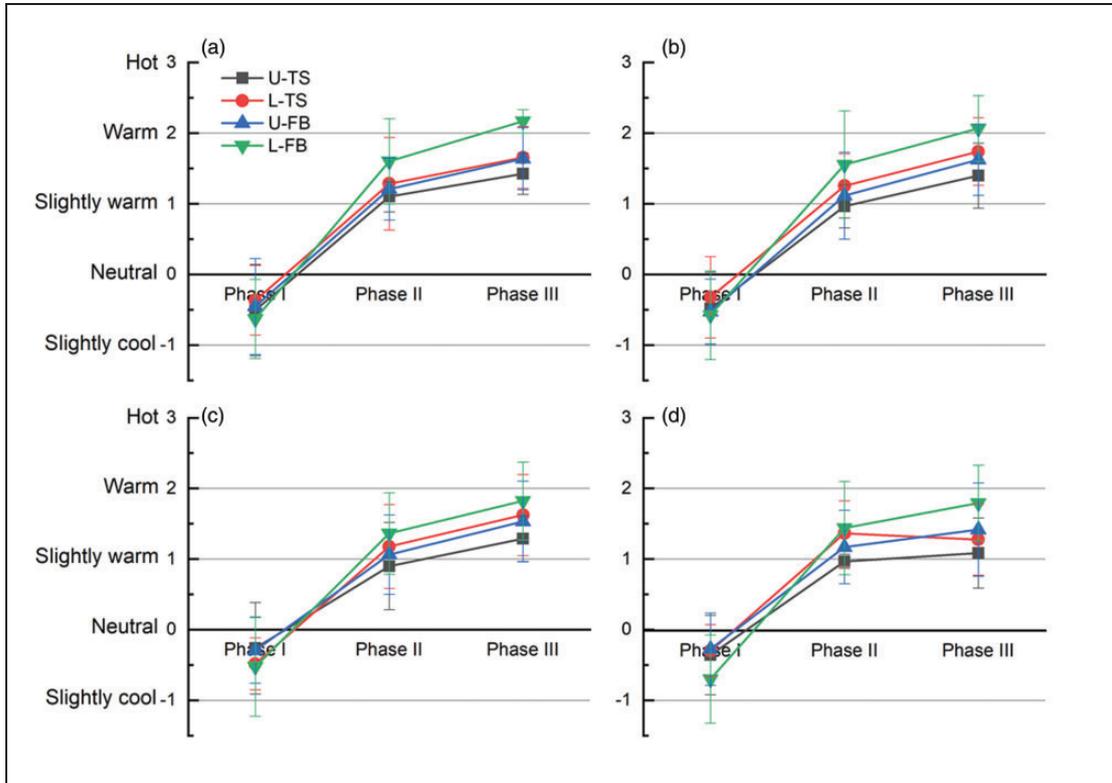


Figure 10. Average subjective ratings during the walking test: (a) whole foot; (b) forefoot area; (c) midfoot area; (d) heel area. U-TS: unloaded with training shoes; L-TS: loaded with training shoes; U-FB: unloaded with firefighting boots; L-FB: loaded with firefighting boots.

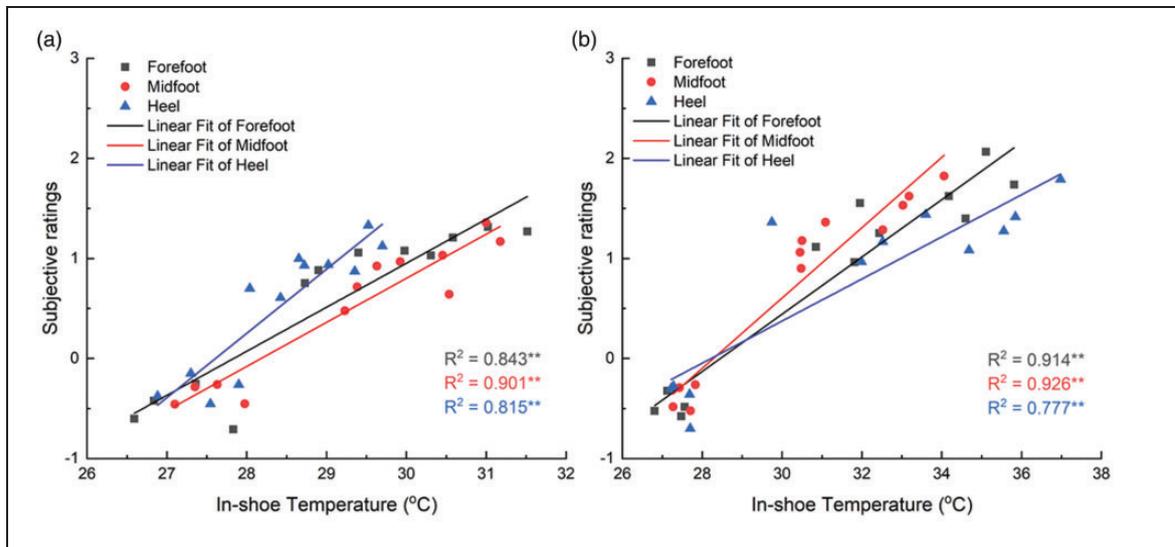


Figure 11. Relationship between mean subjective ratings and mean in-shoe temperatures by foot areas: (a) standing test; (b) walking test. Note: **indicates a statistically significant correlation ($p < 0.01$).

Unlike the standing test, the slope of the midfoot region was the highest (0.351), followed by the forefoot (0.286) and heel (0.210) regions. This indicates that the midfoot region was the most thermally sensitive part of

the foot during the walking test. While the thermal sensation at the midfoot was the warmest, the actual in-shoe temperatures were the same at the forefoot, midfoot, and heel regions.

Table 7. Relationship between mean subjective ratings and mean in-shoe temperatures by test conditions

	Standing test			Walking test		
	R^2	Sig.	Slope	R^2	Sig.	Slope
U-TS	0.735	0.003**	0.389	0.870	<0.001**	0.249
L-TS	0.821	<0.001**	0.374	0.737	0.003**	0.225
U-FB	0.861	<0.001**	0.463	0.863	<0.001**	0.247
L-FB	0.756	0.002**	0.584	0.855	<0.001**	0.304

Note: **indicates a statistically significant correlation ($p < 0.01$).

U-TS: unloaded with training shoes; L-TS: loaded with training shoes; U-FB: unloaded with firefighting boots; L-FB: loaded with firefighting boots.

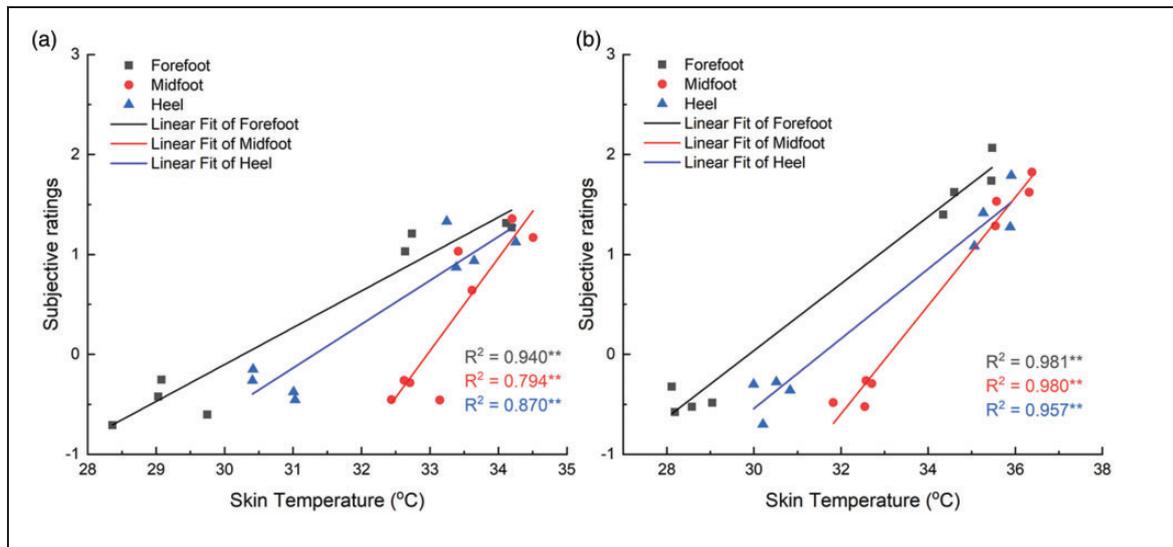


Figure 12. Relationship between mean subjective ratings and mean foot skin temperatures by foot areas: (a) standing test; (b) walking test. Note: ** indicates a statistically significant correlation ($p < 0.05$).

The relationship between mean subjective ratings and mean in-shoe temperatures by footwear/load conditions can be found in Table 7. Statistically significant correlations were observed for all footwear/load conditions during the standing test and walking tests ($p < 0.01$). According to the results of the slope for fitting curves, participants were most sensitive to in-shoe temperature when wearing firefighting boots with a PPE load both in standing and walking tests. The application of a PPE load increased the thermal sensitivity when wearing firefighting boots ($L-FB > U-FB$); however, it reduced the sensitivity when wearing training shoes ($L-TS < U-TS$) for both activities. The perceptual responses were more sensitive to in-shoe temperature when wearing firefighting boots than when wearing training shoes during the standing test ($U-FB > U-TS$; $L-FB > L-TS$). The differences of the slopes in the walking tests were smaller than those of the standing test, indicating that physical activity decreased the effects of the footwear and load.

Relationship between subjective ratings and foot skin temperatures. There was a statistically significant and positive correlation between mean subjective ratings and mean foot skin temperatures in the standing test ($R^2 = 0.617$, $p < 0.001$) and the walking test ($R^2 = 0.808$, $p < 0.001$). Figure 12 presents the fitting curves for these two factors by foot area. In the walking test, thermal sensation scores and foot skin temperatures were highly correlated at all three local foot areas. The slope of the fitting curve at the heel (0.931) was larger than at the forefoot (0.369) and midfoot (0.438) regions, revealing that the thermal response in the midfoot was more sensitive in the standing test. About the walking test, foot perceptual responses and skin temperatures were highly correlated in all foot areas. The slope of the midfoot was the greatest (0.542), followed by the heel (0.349) and the forefoot (0.335). Therefore, the midfoot was the region with the most sensitive thermal sensation in both standing and walking tests.

The subjective ratings and the mean foot skin temperatures by footwear/load conditions are listed in Table 8. Statistically significant correlations were observed for all footwear/load conditions in the walking test ($p < 0.05$). In standing tests conducted using a PPE load (L-TS, L-FB), there was a significant relationship between thermal sensations and skin temperatures. Based on the slope of the fitting curves, participants were most sensitive to skin temperatures when wearing firefighting boots with a PPE load in both standing and walking tests. Following the results of in-shoe temperature, carrying a PPE load elevated the thermal sensitivity when wearing firefighting boots (L-FB > U-FB); however, it decreased when wearing training shoes (L-TS < U-TS) for both activities. Perceptual responses were more sensitive to skin temperature when wearing firefighting boots as opposed to wearing training shoes during walking tests (U-FB > U-TS; L-FB > L-TS).

Table 8. Relationship between mean subjective ratings and mean foot skin temperatures by test conditions

	Standing test			Walking tests		
	R^2	Sig.	Slope	R^2	Sig.	Slope
U-TS	0.452	0.143	0.336	0.821	0.013*	0.317
L-TS	0.715	0.034*	0.288	0.823	0.013*	0.279
U-FB	0.573	0.081	0.333	0.815	0.014*	0.332
L-FB	0.730	0.030*	0.370	0.822	0.013*	0.368

Note: *indicates a statistically significant correlation ($p < 0.05$).

U-TS: unloaded with training shoes; L-TS: loaded with training shoes; U-FB: unloaded with firefighting boots; L-FB: loaded with firefighting boots.

Relationship between local and whole foot subjective ratings.

Subjective ratings were collected for local foot areas as well as the whole foot, as indicated in Figure 13. Significantly and highly correlated relationships were observed in the whole and local areas of the foot. The highest R^2 was found in the heel during the standing test ($R^2 = 0.983$, $p < 0.001$), and in the forefoot during the walking test ($R^2 = 0.996$, $p < 0.001$). The slope of the dashed line illustrated in Figure 13 was 1, which indicated that the subjective ratings of the whole and local areas were equal. During Phases II and III, the slopes at the midfoot and heel were larger than 1, revealing that the subjective ratings of thermal sensation in the whole foot were higher than these two local regions for both activity levels. The relationship between the forefoot region and the whole foot was the same at Phase I, but different at Phases II and III in the standing and walking tests.

Discussion

Temperature formation

According to Shimazaki and Murata,¹² there were two sources of variables that increased the temperature inside footwear, which were heat generated inside the human body itself and heat transferred from the footwear surface. West et al.⁸ also indicated that metabolic heat generation had an impact on the temperature profile in which a rapid and substantial increase in in-shoe and foot skin temperatures was observed during the first 20 min of running. In the current study, higher in-shoe temperatures were observed during the walking test as opposed to when standing. The elevations of

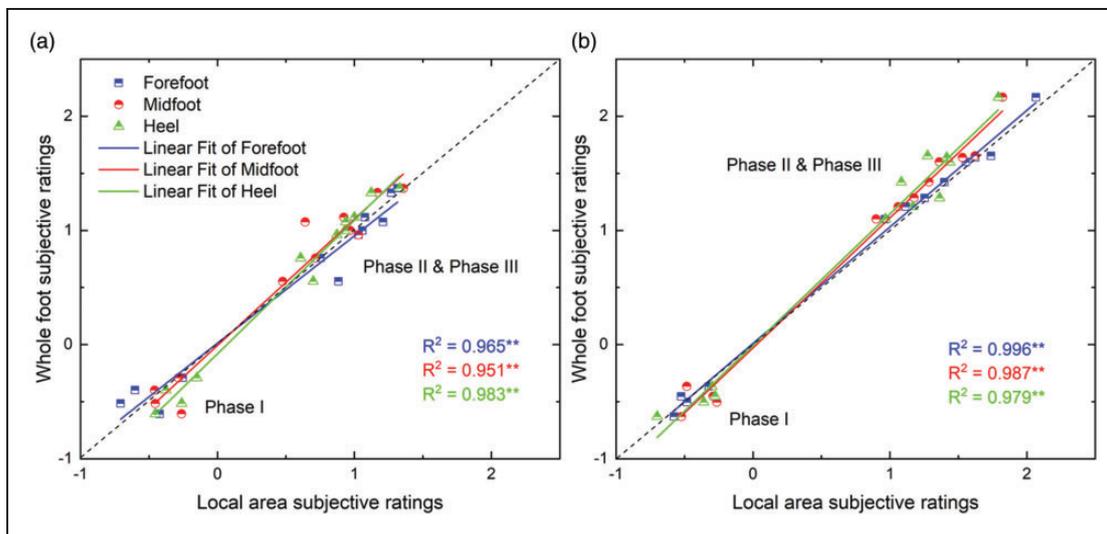


Figure 13. Relationship between local and whole foot subjective ratings of thermal sensation: (a) standing test; (b) walking test. Note: **indicates a statistically significant correlation ($p < 0.01$).

in-shoe and foot skin temperatures in the walking test were also greater than in the standing test, which demonstrated the influences of activity level on in-shoe and foot temperatures. These results correlated with the study of Reddy et al.²² in which walking cadence affected the rate of change of plantar foot temperature.

During the standing test, the in-shoe temperatures in the forefoot and midfoot areas were higher than in the heel area. The elevation of in-shoe temperatures at the forefoot area was the largest, followed by the midfoot and heel areas. The highest increase in foot skin temperatures was found in the forefoot as well, and the value at the midfoot was the lowest. After 20 min walking, elevations in the in-shoe and foot skin temperatures at the heel were higher than those at the midfoot, which was different from the results seen in the standing test. The results of foot skin temperature were in line with the findings of Shimazaki and Murata¹² such that the ball and heel presented higher temperature elevation and the arch presented lower temperature elevation during a gait. The temperatures also increased at standing, but the degree of elevation was close to 0°C at the arch.¹² In our study, the increased skin temperature in the midfoot at standing ranged from 0.5°C (U-TS) to 1.8°C (L-TS, L-FB), which was relatively greater due to a higher air temperature of 32°C in the climate chamber. Faster walking resulted in a larger contact force and higher landing velocity.¹² The temperatures at the ball and heel rose because of heat generation due to foot contact during the gait.¹² West et al.⁸ also highlighted the heel and sole foot regions as the areas of high temperature with running and suggested that the absorption of contact forces on the plantar foot regions, therefore, resulted in temperature elevations. The elevated temperature profile and increased temperatures at the heel in the current study suggested a relationship between the parameters of the heel and the contact force.

Effects of footwear/load conditions on temperature variables

Different patterns of footwear impacts on in-shoe temperature were observed in standing and walking tests based on time-dependent microclimate temperature changes. Shimazaki and Murata¹² reported that temperature elevations were correlated with ventilation. High convective heat transfer would be expected due to foot movement within the shoe and airflow around the footwear.²³ There was no forced convection around the foot during standing in the current study, and the thermal resistance of the footwear played an important role in in-shoe temperature increase. The training shoes, with a greater thermal resistance, showed higher in-shoe temperature elevations than firefighting

boots during standing. However, the midfoot and heel areas exhibited greater temperature increases during walking tests when firefighting boots were worn when compared to training shoes.

On one hand, the weight of the firefighting boots (2.21 kg) was greater than that of the training shoes (0.71 kg). According to the literature, mean increases in metabolic and respiratory variables range from 5% to 12% per 1 kg increase in boot weight for men during the walking test.²⁴ The footwear weight increased the physical burden for the participants. On the other hand, the footwear microclimate conducted was shown to be significantly affected by the footwear permeability.^{7,8} Increased ventilation within running shoes produces a cooling effect, reducing foot skin temperatures, particularly on the arch of the foot.⁸ Increased airflow around footwear during gaits probably has more influence on convection inside the training shoes than the firefighting boots due to the footwear materials. Irzmańska¹³ also indicated the influences of different firefighting boot materials (leather and nitrile rubber) on the temperature of the air surrounding the feet. The footwear effects observed in this study implied that thermal resistance was a more important factor in in-shoe temperature increases during standing. During walking or other activity, in-shoe temperature increases can be controlled by designing the footwear using proper materials with high mechanical strength and light weight, especially for steel toecaps and anti-puncture insoles.

The effects of PPE load on shoe temperature variables are quite consistent. Most of the tests conducted with a PPE load exhibited higher temperature and temperature elevations than tests conducted without a PPE load. Bilzon et al.²⁵ revealed significant increases in energy expenditure for firefighters wearing protective clothing and gear for a given task. Heat stress puts a strain on the vascular system in the lower limbs, increasing body heat and leading to changes in vasomotor tone, causing increases in foot blood flow.¹² The blood flow is approximately 44 cm³/min at an air temperature of 33°C, much larger than that at 20°C (8 cm³/min).²⁰ The in-shoe temperature exceeded 33°C during the walking test in this study. Consequently, the heat delivered by blood flow to the foot most likely caused elevations in the foot skin temperature and the microclimate temperature.^{8,12} Therefore, decreasing the PPE load could effectively reduce the temperature increases in foot skin and footwear microclimate. Footwear/load condition significantly affected elevations of foot skin temperature in the forefoot and midfoot during standing. However, no significant influences were found during the walking test, which indicated that body activity, rather than the physical load, became the predominant factor affecting the foot skin temperature.

Perceptual response and its relation with objective variables

In walking tests, the time-dependent in-shoe temperatures of the training shoes were greater than that of firefighting boots in the forefoot. Lower temperature elevations were observed in the training shoes as opposed to the firefighting boots for most of the test conditions. No obvious pattern was found for footwear effects on increases in the foot skin temperature. However, firefighting boots during the walking test received higher subjective ratings than training shoes, indicating that wearing firefighting boots may elevate the thermal sensation of participants. Although microclimates, as well as foot skin temperatures, contribute to the perception of thermal comfort inside footwear,^{7,8,10,12} heavy work conditions may result in perceptions of the higher temperature inside boots.²⁰ We found that the perceptual responses were more sensitive to skin temperature when wearing firefighting boots than wearing training shoes during the walking test. After the walking test, the average foot skin temperature in the forefoot was the highest, followed by the heel and midfoot. However, the subjective ratings of thermal sensation at the heel were highest and lowest in the forefoot. The probable cause for this may be that the skin temperature was extracted from a single point, whereas the subjective perception focuses on a foot region, which is a limitation of this study. In addition, the differences in the slopes for the walking test were smaller than those of the standing test, indicating that activity level decreased the temperature effects.

Subjective sensations of the foot are strongly correlated with in-shoe and skin temperature in the plantar regions. Strong correlations between foot skin temperature and thermal sensation, and in-shoe temperature and thermal sensations, were observed by West et al.⁸ The findings of their study suggested that 67% of the variance in local thermal comfort can be attributed to foot skin temperature. Both the relationship between perceptual responses and in-shoe temperature, and between perceptual responses and foot skin temperature, indicate that the midfoot was the region with the most sensitive thermal sensation in the human foot during the walking test. The thermal sensation in the whole foot and local areas showed good consistency. According to the slopes of the fitting curves, the thermal sensation at the midfoot and heel was warmer than the whole foot, while the heel was cooler than the whole foot during standing tests. During walking tests, all of the local foot sensations were warmer than the whole foot. Nevertheless, the sensation at the forefoot was closest to the whole foot, followed by the midfoot and heel in both standing and walking tests.

Conclusions

The temperature variables inside footwear are affected by a series of factors, including thermal resistance of the shoes, footwear ventilation, activity level, and physical load. The purpose of this study was to investigate the effects of firefighting boots and PPE load on foot thermal comfort. Four test conditions – unloaded with training shoes, loaded with training shoes, unloaded with firefighting boots, and loaded with firefighting boots – were considered. Human subject wear trials were performed under simulated conditions using a treadmill ergometer. In-shoe temperature and foot skin temperature were monitored at specific foot areas and subjective ratings were obtained during and after testing.

Results indicate that the thermal resistance of footwear plays an important role in footwear thermal comfort during standing. However, more complicated factors, such as the PPE load, footwear weight, and ventilation, would come into play when movement is introduced. During walking or other activity, in-shoe temperature increases can be controlled by adjusting the footwear weight and using proper materials. Although the training shoes provided higher thermal resistance than the firefighting boots, subjective ratings received during walking tests with firefighting boots were higher, indicating that wearing firefighting boots may elevate the thermal sensation of participants. Wearing a PPE load had a significant impact on temperature variables as well as the subjective ratings observed. Decreasing the PPE load could effectively reduce the temperature increases in foot skin and footwear microclimate. Statistically significant correlations with high R^2 between temperature variables and subjective ratings implied that the measured temperatures well represented the thermal perceptions of the participants. The differences in the slopes of fitting curves between objective and subjective characteristics during walking tests were smaller than those seen during standing tests. The thermal sensation at the forefoot was closest to the whole foot, followed by the midfoot and the heel in both standing and walking tests.

The measurements after activity are missing because of using the non-contact infrared thermometers to obtain foot skin temperatures, which is a limitation of this study. Further study should be performed on the relationship of thermal sensation between local areas of the foot and the whole foot. The findings of this study implied negative effects of PPE load on physiological and psychological responses of the human foot. More studies focusing on specific factors are required to improve the functions of firefighting boots.

Declaration of conflicting interests

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