IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 19, 2019, accepted May 6, 2019, date of publication May 10, 2019, date of current version June 3, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2916048

Instrumental Evaluation of Dry Heat Loss of Footwear Under Different Activity Levels

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This work was supported in part by the Innovation and Technology Fund (ITF) with the title "A Novel Microclimate Visualisation System for Enhancing Footwear Design and Comfort" under Grant ITS/107/16 and in part by the PolyU Internal under Grant 1-ZVLJ.

ABSTRACT An extreme microclimate inside footwear contributes to wear discomfort and performance impairment. A thermal foot manikin system was developed to evaluate the thermal insulation of footwear. The uniqueness of this foot manikin is that it utilizes a specially designed all-in-one flexible heating sheet with uneven distribution of resistive wires to achieve a non-uniform gradient temperature distribution along the foot surface. Three flexible heating sheets with different wire distributions were developed to simulate the local skin temperature for different activity levels, suggesting more realistic measures. The heated foot manikin was enclosed by a silicone 'skin' layer, which provides a soft texture. In addition, it was equipped with phalangeal joint and ankle joint for the ease of wearing various types of shoes. The local skin temperature and the power required to heat the foot manikin were recorded. Five types of footwear were compared; the results show that the leather sneaker provides the best thermal insulation performance, whereas the mesh shoe provides the worst thermal insulation performance in walking and running conditions. The findings also reveal that the toe portion is the coolest zone. This paper demonstrated that the measurements from the developed foot manikin are repeatable and versatile, which is useful for optimizing the thermal comfort of the footwear.

INDEX TERMS Thermal insulation, heat transfer, thermal comfort, footwear.

I. INTRODUCTION

Although the feet account for only 7 % of the body surface area [1], their exposure to extreme environments may cause wear discomfort, fatigue, performance impairment or tissue damage [2]. These problems may be more severe for people with insensate feet, e.g., diabetic patients. In addition to the environmental impact, heat balance is affected by the metabolic rate, whereas exercise increases heat production [3], [4]. Some studies have reported that footwear temperatures may increase to 50 °C during exercise in summer [5]. Kuklane [6] mentioned that the footwear temperature should be maintained from 27 to 33 °C for thermal comfort. Heat loss of footwear can be activated by several mechanisms, including conduction through the sole, radiation from surfaces, convection (ventilation) and evaporation through the pores of material and via the openings [7]. Selecting appropriate footwear can protect the feet against hazards and maintain thermal balance of the human body. The insulation properties and ventilation of footwear substantially depends on the construction of the footwear, the fitting, the footwear material (layers, thickness and porosity) and the ability to maintain a still air layer inside the footwear. Depending on the end-uses and wearing conditions, some footwear are designed to keep the feet warm, whereas other footwear are designed to avoid trapping heat.

To characterize the thermal properties of footwear, subjective wearer trials [8]–[11] or objective simulation tests were performed [12]–[16]. Subjective test results can directly relate to real situations of footwear wearing and/or research purposes. However, conducting subjective tests in extreme environments may be dangerous for participants. Subjective assessments are prone to adverse effects by inter-rater and intra-rater variability with numerous uncontrollable and unavoidable noises, and therefore, the repeatability of the results cannot be realized. Since a large sample size is required, these assessments are costly and time-consuming. Objective simulation tests, including material characterization and thermal foot manikins, can be regarded as a substitute for wearer trials. Material characterization can objectively

The associate editor coordinating the review of this manuscript and approving it for publication was Bora Onat.

TABLE 1. Summary of existing foot manikin systems.

Laboratories	Material for foot shell	No. of zones	Skin Temperature	Joints within the foot	Movement	Water supply	Shoe size
TNO Industrial Technology, The Netherlands [17]	water impermeable but water vapor permeable sock	1	Homogenous (25 °C)	no	no	Water vapor	-
National Institute for Working Life, Sweden [18]	plastic	8	Homogenous (30 °C)	no	yes	water	-
Central Institute for Labor Protection, Poland [19]	plastic	9	Homogenous (34 °C)	Ankle joint	yes	water	43
Division of Industrial Ergonomics, Sweden [7]	plastic	9	Homogenous (34 °C)	Toe joint	yes	no	43
EMPA, Switzerland [20]	metal	13	Homogenous (35 °C)	no	yes	water	43
Jožef Stefan Institute, Slovenia [21]	alloy of silver and copper	16	Homogenous (35 °C)	no	no	water	-
Jožef Stefan Institute, Slovenia [22]	alloy of silver and copper	10	Homogenous (35 °C)	no	yes	Water vapor	-
Thermetrics, USA [23]	highly conductive carbon epoxy	12	-	Ankle and toe joints	yes	Water	42
Footwear Technology Centre of Portugal, Portugal [24]	aluminum	7	30-34 °C	-	no	Water	-

evaluate the performance of a particular material. However, it cannot analyze the effect of footwear design, air gap, fitting, construction and production methods [17]. A thermal foot manikin, which enables repeatable measurement of footwear of various designs, is preferred. Foot manikins for simulating the thermoregulatory system of a human are useful for quantifying the heat exchange between the foot and the surrounding environment and predicting the thermal comfort [25]. A summary of existing foot manikin systems is shown in Table 1. Most of these systems are constructed of heat conductive metal to create a uniform temperature over the surface of a foot manikin [20]–[22], [24]. The skin temperature is homogeneous along a foot manikin [7], [17]–[22], which may not simulate human foot physiology. Some foot manikin systems are divided into several zones, and each thermally isolated zone enables independent control of temperature. However, the temperature distribution in these thermally isolated regions remain different from human foot physiology, in which gradual changes in skin temperature occur between two zones. Independent electrical supplies have to be connected to each region, which increases the complexity and cost of a foot manikin system. The majority of foot manikins are not equipped with joints, which restricts the type of footwear that can be worn due to the rigidity of the foot manikin [17], [18], [20]–[22]. Although foot manikins are the most useful tools for evaluating the thermal comfort of footwear, their use is not prevalent in laboratories due to their high cost. Against these research backgrounds, the objective of the current project is to develop a foot manikin system that (i) offers a gradient temperature distribution along the foot that simulates the human foot physiology for different activity levels, (ii) is capable of testing various types of footwear, and (iii) is cost-effective. This study examined the thermal insulation and microclimate of various footwear with respect to changes in activity levels. The repeatability and validity of the measurement is further investigated. This foot manikin system is useful for product development in terms of thermal comfort.

II. METHOD

A. PRINCIPLE OF FOOT MANIKIN SYSTEM

The foot-shaped unit was mounted with a specially designed flexible heating sheet and covered with a silicone layer that acts as 'skin'. The distribution and thickness of resistive wires within the heating sheet are uneven to achieve a non-uniform gradient temperature distribution along the foot. In general, closely packed thinner wires can achieve a high temperature, and vice versa for lower temperature regions. To simulate the skin temperature at different activity levels, a series of heating sheets with different heating power for different segments were developed. The heating sheet is exchangeable by removing it from the silicone skin and substitution with the selected heating sheet. To further imitate the wearing condition with foot movement, the foot manikin was blown with wind. The air velocity around the foot manikin corresponds to the speed of foot movement (e.g., walking or running speed). Temperature sensors were attached to the skin to monitor the temperature change with regard to different end-uses. The dorsal skin of the foot was controlled at a predetermined temperature and the power required to maintain the skin at specific temperatures was additionally recorded. The results measured by this foot manikin system are affected by the footwear properties, wind velocity and local skin temperature.

B. HARDWARE CONFIGURATION AND THE MECHANISM

The footwear measurement system consists of four key components: (i) the foot manikin, (ii) the chamber, (iii) the data acquisition system, and (iv) the power source. A schematic of the foot manikin is depicted in Fig. 1, whereas the entire footwear evaluation system is illustrated in Fig. 2.

Regarding the foot manikin, a foot-shaped unit (1) that was 3D-printed with polyether ether ketone (PEEK) and equipped with a metatarsal phalangeal joint (3) and ankle joint (4) for the ease of wearing various types of shoes. The joints anatomically divided the foot model into three parts (toe, foot and calf). The toe portion was connected to the remainder of the

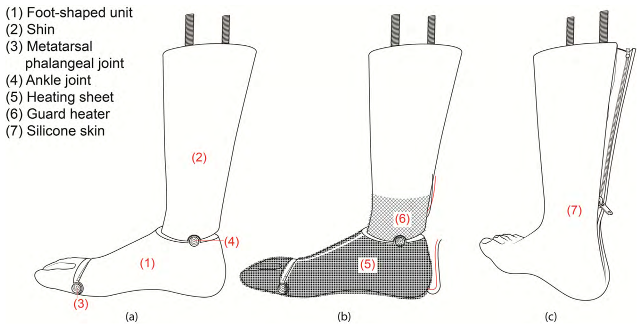

FIGURE 1. **Schematic of the main components of the foot manikin. (a) 3D-printed foot model with metatarsal phalangeal joint and ankle joint, (b) foot manikin with attached heating components, and (c) foot manikin enclosed by silicone skin.**

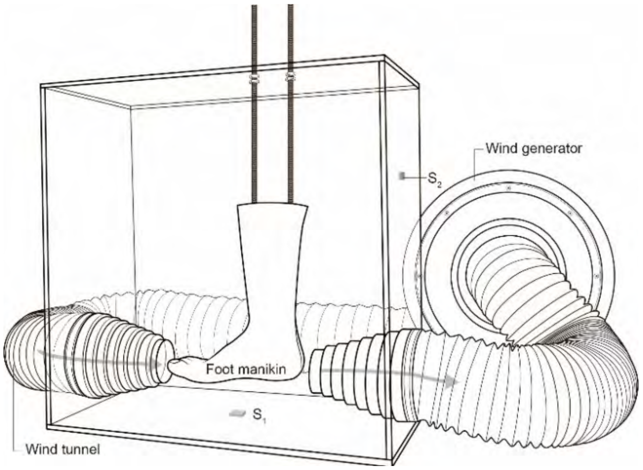

FIGURE 2. **Schematic of the entire setup of the foot manikin system with the direction of air flow represented by arrows. S1 and S2 are the temperature and humidity sensors inside the box.**

foot-shaped unit (1) via a metatarsal phalangeal joint (3), whereas the foot-shaped unit was connected to the shin (2) via an ankle joint (4). A flexible heating sheet (5) was embedded in the foot-shaped unit (1) for heat supply. If the shin (2) was not heated, the temperature gradient between the shin (2) and the foot (1) will be large and the power required to heat the foot unit (2) will be overestimated. To minimize vertical heat transfer flow from the foot unit (1) to the shin (2), this foot manikin system was equipped with a guard heater (6). The temperature of the guard heater (6) was close to the upper part of the foot unit (1) in order to maintain the isothermal condition in this region. Measurements from the guard heater (6) were not employed for data analysis. The foot unit (1) and the heaters (5 and 6) were enclosed by the silicone prostheses (7) (REGAL®) that act as 'skin'. As shown in Fig. 1(c), the silicone skin was fastened by an invisible zipper for the ease of wearing. The total length of the foot manikin is 24 cm. The dimension of the foot model was with reference to the foot anthropometric measurements of 49 female Chinese adults. The effective surface area of the heated foot manikin (to the ankle point) is 537.5 cm^2, as measured using 3D laser scanning and image analysis.

As shown in Fig. 3, the foot model was divided into 14 zones, and the surface area and surface area ratios of

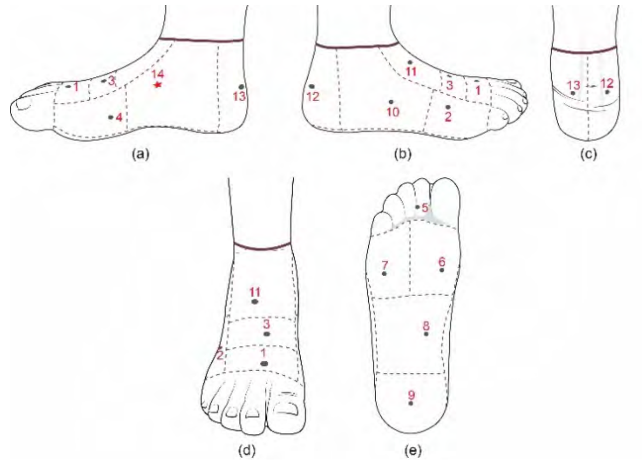

FIGURE 3. **Dashed lines divided the foot manikin into 14 zones, whereas the grey circles and red star denote the positions of 14 thermocouples. The red star indicates the thermocouple that connects to the temperature controller.**

TABLE 2. **Surface area of each zone.**

Zone no.	Segment	Surface area (cm^2)	Surface area ratio (A_i) [a]
1	Dorsal (front)	18.55	0.035
2	Lateral (forefoot)	23.57	0.044
3	Dorsal (instep)	17.71	0.033
4	Medial (forefoot)	20.00	0.037
5	Forefoot (neck of toe)	81.96	0.152
6	Plantar forefoot (metatarsal head)	23.82	0.044
7	Plantar (lateral)	26.52	0.049
8	Plantar (arch)	47.27	0.088
9	Plantar (heel)	38.16	0.071
10	Lateral (mid-foot)	55.02	0.102
11	Dorsal (instep)	41.10	0.076
12	Rear	39.67	0.074
13	Rear	45.80	0.085
14 (Set-point)	Medial (mid-foot)	58.40	0.109

[a] Based on the effective surface area of the foot manikin (537.5 cm^2).

each zone are summarized in Table 2. The calculation of surface area ratio is shown in (1). Each zone was attached with a thermocouple (RS Pro); its placement location is marked in Fig. 3. The local skin temperature against time was recorded. The dorsal skin of the foot (a red star in Fig. 3) was controlled at a predetermined temperature and the power required to heat the foot was additionally recorded. The choice of heating sheet and wind velocity in accordance with the simulated physiological conditions for different activity levels and their effect on the foot skin temperatures can be evaluated.

As shown in Fig. 2, the foot manikin was hanged within a sufficiently large chamber (L: 60 cm, W: 32 cm, H: 60 cm), where the wind velocity can be regulated and disturbance of air movement can be minimized. Uniform wind was generated by a centrifugal fan that blew wind through the wind tunnel (W: 16 cm), the nozzle and from the toe region to the heel (i.e., horizontal air movement along the footwear). Another nozzle was positioned next to the heel of the foot manikin for air suction. The airflow velocities at different regions of the shoe surfaces and at different time points were measured for verification. With the use of closed loop air ducts, uniform airflow was achieved as the deviation of these velocities was below 10% in each test. Constant air flow around the immobile foot manikin imitates wind moved around a moving foot. The wind speed is adjustable to simulate various foot movement levels.

$$Surface\ area\ ratio\ (A_i) = \frac{Surface\ area\ of\ a\ particular\ zone}{Surface\ area\ of\ the\ foot\ manikin} \quad (1)$$

The data acquisition system (DAQ) was equipped with a temperature input module, humidity input module and digital module. The temperature input module was used to measure the local skin temperature (14 points) and ambient temperature (2 points inside chamber). The humidity input module was used to measure the humidity within the chamber. The digital input module was utilized to control the on/off function of the heater (5). PID (proportional-integral-derivative) control programming was used which monitored the actual temperature of the temperature sensor and adjusted the power in real time. This allowed the surfaces to reach the desired target temperature with a high degree of accuracy in the minimum amount of time. For the power source, 12 V power was connected to the heating sheet (5). Additionally, the DAQ collects the data twice per second and sends the data to the computer interface for recording. All data will be recorded by Excel using the macro function.

C. EXPERIMENTAL SETTING

1) DETERMINATION OF THE LOCAL SKIN TEMPERATURE OF HEATING SHEET

A wearer trial was performed to investigate the skin temperature for different activity levels. This information helps to determine the wire distribution of the heating sheets. Informed consent was obtained prior to the start of the wearer trial. Twenty-four female healthy volunteers and sixteen male healthy volunteers, aged between 19 and 39, were screened for the subjective assessment. The experimental protocol, as approved by the Research Ethics Committee of Hong Kong Polytechnic University, includes 30 min stabilization, followed by 20 min sitting + 20 min resting, 30 min walking + 30 min resting or 30 min running + 30 min resting. The sequence of sitting, walking and running is randomized and each participant was asked to perform these activities in barefoot conditions while long-sleeved cotton T-shirt and trousers were worn. No alcohol, caffeine or medical drugs should be taken 48 hours before testing. Walking and running were performed on a treadmill while all tests were conducted in a climatic chamber: air temperature 22.5 ± 1 °C and 65 ± 5% RH. A thermal infrared camera (FLIR T420bx) was kept perpendicular to the interested side of the foot at a distance of 0.85 m and was used to capture the foot image immediately after various activities.

Correlation analysis was performed to investigate the correlation between the wearer trial results and the foot manikin measurements. A relatively high and positive correlation was observed (Pearson's $r = 0.898$ for the sitting condition, Pearson's $r = 0.696$ for the walking condition, and Pearson's $r = 0.796$ for the running condition). This finding suggests that the temperature distribution of the foot manikin can adequately mimic real situations.

According to the wearer trial measurements from the forty participants, the set-point temperatures for the sitting, walking and running conditions were 28 °C, 30 °C and 33 °C, respectively. The guard heater was maintained at the same temperature level.

2) DESIGN OF HEATING SHEET

The all-in-one heating sheet was specially designed to fully cover the foot (the sole, the instep, the heel and the toes) and conform to the 3D foot model. The orientation, density and thickness of the resistive wires was systematically configured and allocated to match the temperature requirement and achieve a non-uniform gradient temperature distribution among different locations of the foot. Considering the toe portion as an example, thinner wires were placed at larger intervals; thus, the toe portion is generally cooler than the remainder of the foot unit.

Given the same environmental conditions, the metabolic rate varies with activity level and determines the heat production. For example, the metabolic rate for sitting is 55 W/m^2, whereas the metabolic rate for walking at 2 km/h and 5 km/h are 110 W/m^2 and 200 W/m^2, respectively [26]. The activity level is a dominant factor that affects the magnitude and distribution of local skin temperature, and thus a series of heating sheets with different wire distributions at different regions were designed. Three heating sheets that simulate sitting (i.e., static), walking (i.e., mild activity level) and running (i.e., moderate activity level) conditions were examined in this investigation. The resistive wires at different regions of the heating sheet are connected. Unlike the foot manikins in which different temperature zones were divided by insulating membranes, no abrupt change in temperature was observed between any two zones. Instead, the temperature gradually changed. The thermal imaging of the foot manikin with three different heating sheets are shown in Fig. 4. The first column shows the thermal imaging of the sitting foot for different perspectives, whereas the second column and third column show the temperature distribution of the walking foot and the running foot, respectively. The 'running foot' is generally hotter than the 'sitting foot' and the 'walking foot'.

3) ENVIRONMENTAL CONDITION

The foot manikin test was performed in conditioned environment that was maintained at 23±0.5 °C and 65±5% RH. The air velocity was controlled by the wind generator and ranged from 0.3 to 3 m/s. Airflow of 1.1 m/s and 2.8 m/s corresponds to walking at 4 km/h and running at 10 km/h [3], respectively.

4) MATERIAL FOR THE OUTER LAYER OF THE FOOT MANIKIN

Silicone rubber was selected as the outer layer, which is flexible and compressible and has a texture that resembles that of human skin. Its thermal conductivity is approximate to that of human skin whereas its specific heat, even though

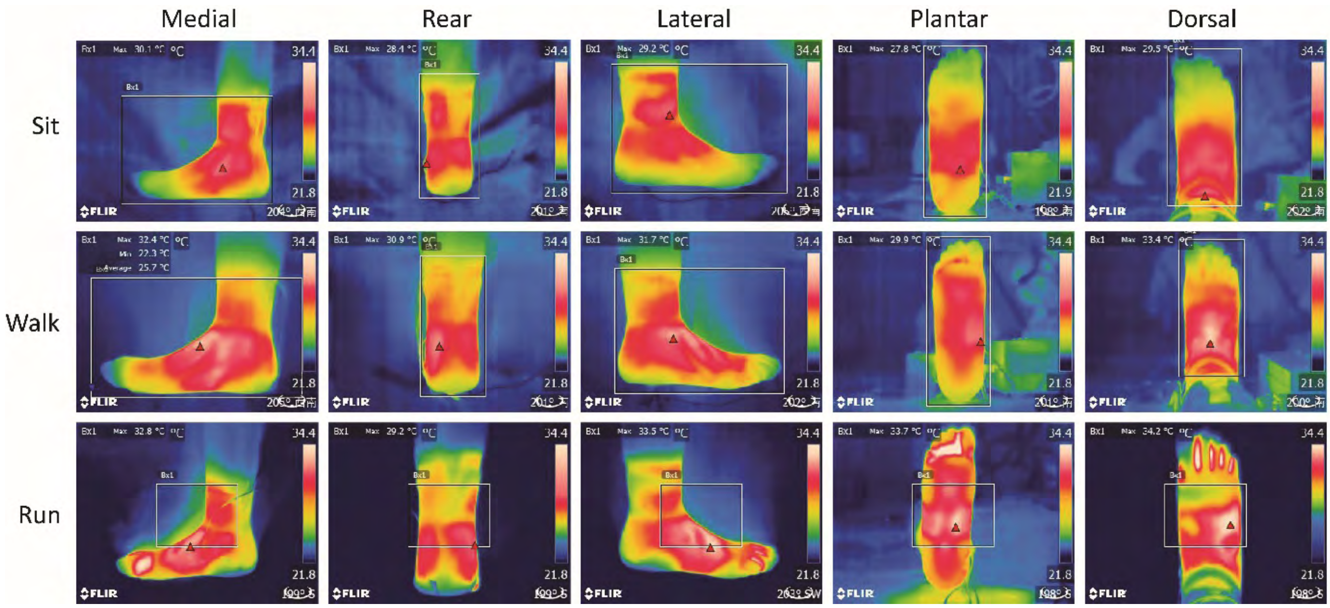

FIGURE 4. **Thermal imaging of the heated foot manikin in barefoot conditions from different perspectives. Photos were taken after 3 hrs stabilization. Emissivity set value = 0.97.**

TABLE 3. **Thermal properties of human skin and various materials that are generally used for foot manikin's shell.**

	Thermal conductivity (W/m.K)	Specific heat (J/kg.K)	References
Skin	0.3-0.4	3390	[27-29]
Polyvinylchloride, PVC	0.19	840 - 1170	[30, 31]
Copper	401	385	[30, 31]
Silver	419	234	[30, 31]
Aluminum	210	900	[30, 31]
Silicone rubber	0.1-0.3	1050-1300	[32]

it is three times lower than the human skin, is much higher than other metal, as supported by the value shown in Table 3. The hardness of human skin ranges from approximately 20 A to 60 A [33], and the hardness of our silicone foot prostheses is 50 A. Therefore, the use of silicone rubber as the outermost layer provides a more realistic stimulation than foot manikins constructed of metal. The soft and flexible skin features enable the foot to be fitted into footwear with different structures and designs, which range from traditional protective boots to fashionable shoes.

5) TESTING PROCEDURES

The heating sheet was selected, fixed onto the foot unit and then enclosed by the silicone skin layer. The thermocouples were attached onto the specified position of the skin surface. The set-point temperature was pre-set, and the footwear was directly put on the foot manikin. No socks were worn to simplify the experiment. Regarding the testing condition, in which wind is required, the wind generator will be switched on at this stage. Upon activation of the heating element, a non-uniform gradient temperature distribution across the foot surface was gradually achieved.

Changes in skin temperature, footwear temperature and energy required to maintain the target temperature at predetermined level were measured and continuously recorded for 4 hrs and 40 min. The first 3 hrs is the stabilization period to ensure that the surface temperature and heat loss were in a steady state. The subsequent hour is the measurement period. After this period, the heater will be switched off and the temperature decrease in skin temperature will be recorded for 40 min. Each test was repeated three times to determine the repeatability of the method.

D. MEASUREMENT PARAMETERS

1) SKIN TEMPERATURE

The local skin temperature was recorded against time. The area-weighted mean foot temperature (T_s) was calculated according to (2) and based on the local skin temperatures of the 14 divided skin areas, which were measured by 14 temperature sensors attached to the manikin's skin. Fig. 3 shows the locations of the 14 temperature sensors. The surface area ratios of the divided sections is shown in Table 2.

$$\boldsymbol{T_S} = \sum_{i}^{n} A_i T_{si} \tag{2}$$

where A_i is the surface area ratio for a division of the manikin skin surface, and T_{si} is the temperature of a division of the manikin surface area (°C).

2) TOTAL THERMAL INSULATION

The total thermal insulation of the footwear or the barefoot condition (R_t) is calculated by (3).

$$\boldsymbol{R_t} = A(T_s - T_A)/\mathrm{H} \tag{3}$$

where R_t is the total thermal insulation of the footwear and the boundary air layer ($°C \cdot m^2/W$); A is the effective surface area of the foot manikin, which is 0.05375 m^2; T_S is the area-weighted mean foot temperature; T_A is the temperature of the

TABLE 4. Specifications of various footwear.

Code	Shoes upper			Size	Weight	Cover area (cm^2)	Surface area of shoes
	Material	Fabric construction	Thickness (mm)		(g)		(cm^2)[a]
MESH	Polyester	Air mesh	1.94	40	136	494	769.66
LEATHER	Genuine leather, foam	Non-woven	5.75	40	200	499	825.77
KNIT	Cotton	Knitted	2.50	40	295	482	766.26
CANVAS	Cotton	Plain-weave	1.00	40	323	414	726.19
SLIPPER	Polyester, foam	Knitted	4.36	40	104	496	747.72

[a]refer to area exposed to the external environment.

FIGURE 5. Images of various footwear. (a) MESH, (b) LEATHER, (c) KNIT, (d) CANVAS, (e) SLIPPER.

surrounding environment; and H is the dry heat loss of the foot manikin (W). The total thermal insulation corresponds to the power required to heat the foot manikin during the steady-state period.

3) INTRINSIC THERMAL INSULATION OF THE FOOTWEAR

Intrinsic thermal insulation is determined by subtracting the air layer resistance around the footwear-covered manikin from the total insulation value for the ensemble, as calculated by (4).

$$\boldsymbol{R_{ft}} = R_t - R_a/f_{ft} \tag{4}$$

where R_a is thermal resistance of the air layer on the surface of the foot manikin in the barefoot condition (°C · m^2/W), and f_{ft} = footwear area factor (dimensionless).

Similar to the clothing area factor, the footwear area factor may be related to the fitting, design and thickness of the footwear. Varying the surface area of the footwear affects the heat exchange between the foot and the surrounding environment. The footwear area factor (f_{ft}) is determined using (5).

$$\boldsymbol{f_{ft}} = A_{ft}/A \tag{5}$$

where A_{ft} is the surface area of the foot manikin with footwear worn, and A is the surface area of the foot manikin in the barefoot condition. Rapidform XOR software was used to calculate the surface area of the footwear and the foot manikin.

4) PERCENTAGE OF TEMPERATURE DROP IN FOOT TEMPERATURE AFTER POWER-OFF

After switching off the heater, the local skin temperature is continuously recorded. The percentage of temperature decrease after power-off for 40 min (TD%) is calculated by (6).

$$\boldsymbol{TD\%} = (T_{SM} - T_{S40})/T_{SM} \times 100\% \tag{6}$$

where T_{SM} is the area-weighted mean foot temperature before power-off, and T_{S40} is the area-weighted mean foot temperature after power-off for 40 min.

III. SAMPLE SPECIFICATIONS

Five footwear of EU size 40, with the insole removed for the ease of comparison, were conditioned in the testing atmosphere for at least 24 hrs prior to testing. The specifications of these five footwear are summarized in Table 4 and their corresponding images are shown in Fig. 5. 'MESH', 'LEATHER', 'KNIT' and 'CANVAS' are sneakers for everyday use, whereas 'SLIPPER' is an open-toe slipper for indoor use. To maintain a constant fit of the footwear, all footwear were carefully laced to obtain a similar tension each time.

IV. RESULTS AND DISCUSSION

A. SKIN SURFACE TEMPERATURE DISTRIBUTION

Table 5 lists the local skin temperature distribution of the foot manikin for various conditions. Depending on whether wind is supplied, which heating sheet is utilized and which footwear is worn, the local skin temperature varies. In general, the arch (#8), medial (mid-foot, #14), and instep (#3, #11) are the hottest regions. The forefoot, particularly the toe region (#5), is the coolest, whereas the lateral side (#2, #10) shows moderate temperatures.

B. INVESTIGATING THE USAGE OF THE FOOT MANIKIN SYSTEM

To investigate whether the foot manikin is capable of differentiating the thermal properties of various footwear, a two-way analysis of variance (ANOVA) between-groups was performed with activity level and footwear defined as the independent variables. The ANOVA aims to determine if significant differences in the mean scores exist across the three activity levels and the five footwear. All statistical data were analyzed by SPSS 22.0. The significance level was 0.05.

Table 6 shows the ANOVA test results, which indicate that the interaction effect of activity and footwear is significant

TABLE 5. Local skin temperature (°C) of the foot manikin in various conditions*.

		Medial		Lateral		Rear		Front			Plantar				
		Port-4	Port-14	Port-2	Port-10	Port-12	Port-13	Port-1	Port-3	Port-11	Port-5	Port-6	Port-7	Port-8	Port-9
Sit	BAREFOOT	25.72	28.06	25.71	26.34	26.25	26.25	24.34	26.74	27.58	23.19	25.03	24.94	27.15	24.98
	MESH	25.90	28.10	25.70	26.38	25.79	25.99	24.30	26.75	27.56	23.31	25.08	25.21	27.63	25.81
	LEATHER	25.50	28.10	25.15	26.35	25.73	25.59	24.00	26.55	27.47	22.82	24.45	24.55	26.64	25.05
	KNIT	25.68	28.08	25.44	26.36	26.26	26.20	24.25	26.44	27.30	23.27	25.24	25.12	27.85	25.77
	CANVAS	26.35	28.07	25.86	26.37	25.60	25.65	24.45	27.14	27.94	23.28	25.33	25.59	28.67	26.06
	SLIPPER	28.12	28.08	28.61	28.56	27.21	26.83	25.91	29.06	28.19	23.91	27.44	27.88	31.17	27.89
Walk	BAREFOOT	31.13	29.98	27.83	30.50	31.75	29.04	26.94	26.36	28.52	25.44	28.45	29.68	28.57	27.99
	MESH	28.46	30.03	28.81	28.70	28.43	29.72	26.48	29.62	27.35	25.99	30.15	29.36	32.45	30.57
	LEATHER	28.02	30.05	28.18	28.96	27.54	28.47	27.57	30.38	30.85	25.24	28.11	27.43	29.91	27.93
	KNIT	29.78	30.03	28.10	28.95	28.05	29.50	27.52	28.73	29.12	26.04	30.63	28.96	33.49	29.61
	CANVAS	29.68	30.03	28.06	28.28	26.60	27.55	27.70	29.90	30.21	26.22	29.63	28.74	32.57	28.90
	SLIPPER	35.42	30.03	35.43	32.40	29.60	29.44	30.56	35.80	32.27	26.33	36.22	34.76	39.32	34.26
Run	BAREFOOT	31.42	32.90	30.31	29.31	28.03	25.03	31.23	30.56	32.65	25.77	29.02	31.40	33.47	26.37
	MESH	29.61	32.53	29.87	30.46	29.75	28.98	29.38	28.93	30.73	33.67	28.81	34.77	32.92	30.06
	LEATHER	31.17	33.05	31.47	30.73	28.49	28.11	30.21	32.55	32.56	30.04	30.17	31.06	32.03	27.61
	KNIT	31.10	33.04	31.17	30.54	29.03	28.97	29.12	30.37	31.85	31.83	31.29	33.19	35.17	29.03
	CANVAS	32.00	33.03	30.33	28.41	27.26	27.51	30.01	32.04	31.99	31.83	31.08	33.75	34.49	28.10
	SLIPPER	35.62	33.04	36.63	31.91	28.24	28.26	31.28	36.23	32.47	32.60	33.25	37.50	35.53	31.47

*Color scale	≤26	26<x≤27	27<x≤28	28<x≤29	29<x≤30	30<x≤31	31<x≤32	32<x≤33	33<x≤34	34<x≤35	x≥35

TABLE 6. Tests of between-subjects effects result.

	T_S		R_t		R_{ft}	
Source	F	Sig.	F	Sig.	F	Sig.
Activity	8023.66	0.000	668.44	0.000	98.54	0.000
Footwear	695.40	0.000	262.28	0.000	275.99	0.000
Activity* footwear	47.31	0.000	32.59	0.000	33.41	0.000

in average skin temperature ($p < 0.05$), R_t ($p < 0.05$) and R_{ft} ($p < 0.05$). This finding implies that the effect of footwear depends on which activity level is being considered and the effect of activity depends on which footwear is being considered. For example, 'MESH' had a moderate performance in R_t for the sitting condition (3rd of the 5 footwear); however, the lowest R_t was obtained for the walking and running conditions. Due to the significant interaction effect, we will separately examine the effect of each subgroup, and post hoc tests with the Scheffé technique were conducted to compare the effect of footwear on each activity level and the effect of activity level on each footwear. The pairwise comparison results for different footwear and different activity levels are summarized in Table 8 and Table 9, respectively.

1) EFFECT OF FOOTWEAR

Regardless of the activity level, the area-weighted mean foot temperature in the 'SLIPPER' condition is significantly higher than that of other footwear ($p < 0.05$; refer to Fig. 6(a) and Table 8) as 'SLIPPER' is constructed of a relatively thick layer of foam. The air gap within the foam is a suitable thermal insulator; thus, it can minimize heat loss of the foot. Since heat is dissipated into the environment through the shoe material due to convection, the choice of footwear material and design of footwear have major impact on heat dissipation and in-shoe temperature. The in-shoe temperature of 'SLIPPER' could be readily affected by external environment (air velocity) or human motion (activity level) due to its open-toe design. As compared to walking, the wind velocity generated during running facilitates faster heat transfer from the inside of the 'SLIPPER' to the outside through the foam and the open-toe design. Hence, the foot plantar temperatures (including Port-8) during walking were higher than that during running in 'SLIPPER'.

Regarding the thermal insulation properties (R_t and R_{ft}), the 'LEATHER' footwear achieved the best thermal insulation properties irrespective of the activity level (refer to Fig. 6(b) and (c)). Higher thermal insulation values can be attributed to the air resistance and fabric thickness, which imposes a barrier to heat transfer. The thermal insulation performance of 'SLIPPER' is slightly worse than that of 'LEATHER'. For the 'MESH', its fabric has an open structure and the air gap within the mesh fabric is an excellent source of thermal insulation in static conditions. Thus, its thermal insulation properties are significantly higher than 'CANVAS' and 'KNIT' in the sitting condition ($p < 0.05$). However, once wind circulation occurs around the 'MESH' footwear, cool air can pass through its pores and easily reach the skin, which is less effective for preserving the foot temperature; thus, its thermal insulation properties deteriorate. The R_t and R_{ft} are significantly lower than those for 'KNIT' ($p < 0.05$) but are similar to 'CANVAS' ($p > 0.05$) in the walking condition. When the wind velocity increases (i.e., the running condition), its R_t and R_{ft} are substantially lower than all other investigated footwear ($p < 0.05$).

The reduction in R_t between the sitting condition and the walking condition was 67.7 % for the barefoot condition, 45.4 % for 'MESH', 22.4 % for 'LEATHER', 22.4 % for 'KNIT', 28.7 % for 'CANVAS', and 38.4 % for 'SLIPPER'. Among the five footwear, the reduction in R_t is particularly high for 'MESH', which can be attributed to the large pores within the fabric and its excellent air permeability, facilitating convection and heat dissipation. For 'LEATHER', its air resistance is particularly high. Heat cannot penetrate the voids

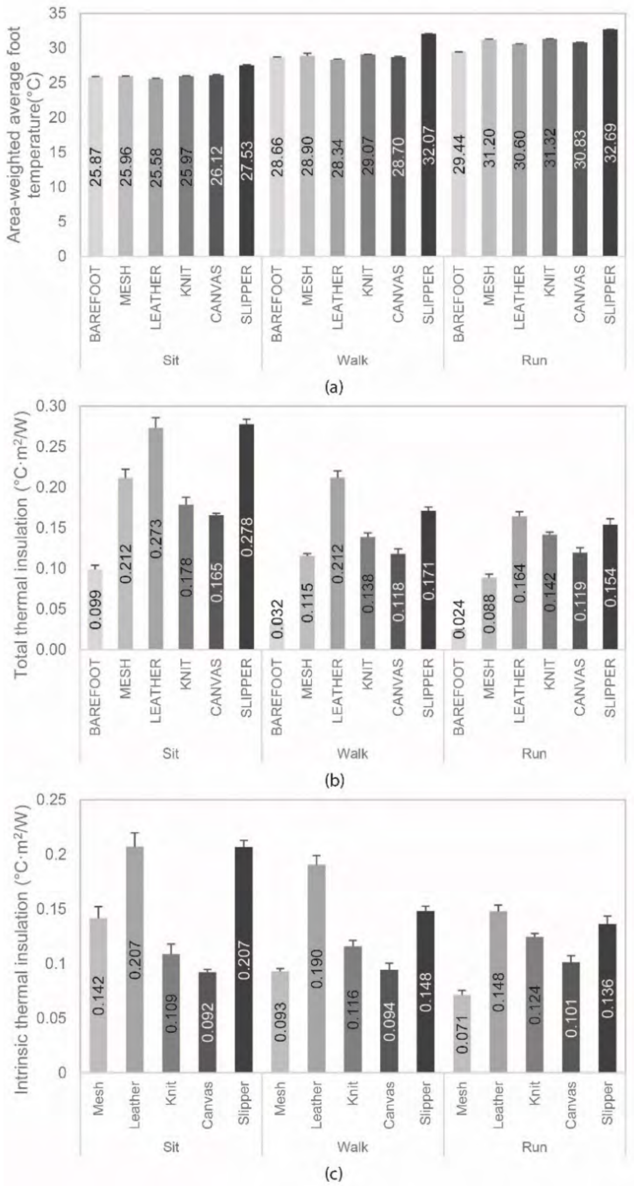

FIGURE 6. **Foot manikin results. (a) Area-weighted mean foot temperature when wearing different footwear at different activity levels; (b) Total thermal insulation of various footwear for different activity levels; and (c) Intrinsic thermal insulation of various footwear for different activity levels.**

in the footwear, which disturbs heat transfer by convection. Therefore, even though it is blowing in the 1.1 m/s wind condition, minimal reduction in R_t occurs.

2) EFFECT OF ACTIVITY LEVEL

Based on the wearer trial results, the set-point temperature increases with activity level, which produces differences in the area-weighted mean foot temperature. For the sitting condition, the area-weighted mean foot temperature ranges from 25.58 °C to 27.53 °C. For the walking condition, the area-weighted mean foot temperature ranges from 28.34 °C to 32.07 °C, which is 11.9 % higher than those for the sitting condition. With more strenuous exercise (i.e., the running condition), the area-weighted mean foot temperature is even higher, ranges from 29.44 °C to 32.69 °C and is 18.5 % higher than the sitting condition.

Among the three activity levels, the R_t of the sitting condition is significantly higher irrespective of the footwear type. For the no-wind condition, the footwear is covered by a relatively thick layer of claim air. Clam air is an excellent thermal insulator; its thermal conductivity is approximately 0.025 W/mK [21]. Walking and running incorporate significant airflow to cool the foot, eliminate the still surface air layer and increase convective heat dissipation. The regulator needs to increase the given power when wind is applied and when the set-point temperature is higher. Thus, increasing the exercise level tends to decrease the total thermal insulation of footwear, as observed in Fig. 6(b).

C. RELATIONSHIP BETWEEN R_t AND TD%

Heat transfer occurs when a temperature difference exists between two surfaces. When the ambient temperature is lower than the skin temperature, the skin temperature tends to decrease. The rate of temperature decrease depends on the temperature gradient and the footwear material, and a well-insulated footwear can restrict heat loss. As shown in Fig. 7, the thermal insulation and percentage of temperature decrease after power-off for 40 min are negatively related ($R^2 = 0.50$).

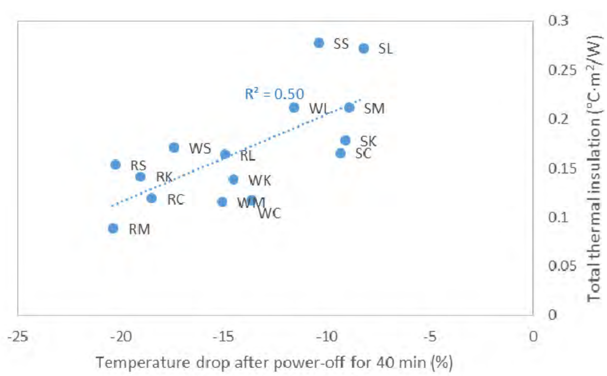

FIGURE 7. **Correlation between R_t and TD%. The first character of the data label denotes the activity level (S = Sit, W = Walk and R = Run), and the second character denotes the footwear type (M = MESH, L = LEATHER, K = KNIT, C = CANVAS and S = SLIPPER).**

Higher temperature loss is associated with lower thermal insulation value; this finding is rational and suggests that TD% can provide an estimation of the thermal protection of footwear.

D. RELATIONSHIP BETWEEN R_t AND f_{ft}

As shown in Fig. 8, the total thermal insulation and footwear area factor are positively related. The slope is more gradual in the running condition (slope = 0.267) than the slope in the walking condition and sitting condition

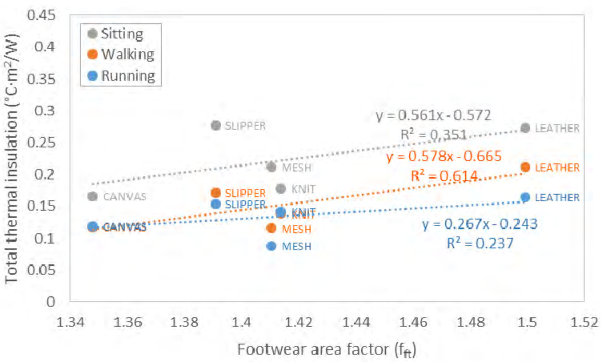

FIGURE 8. Relationship between R_t and f_{ft} for different activity levels.

of 0.578 and 0.561, respectively. For the no-wind condition (without human motion), R_t is sensitive to the change in footwear area factor (i.e., steeper slope) and related heat dissipation to the outside environment. Footwear with a high f_{ft} has a reasonable boundary air layer in which the in-shoe temperature can yield a high value of R_t. The movement of air during dynamic movement disturbs the formation of an air layer in which the impact of f_{ft} on $R_t$considerably decrease in the windy condition.

'MESH' and 'KNIT' have similar f_{ft}($\sim$ 1.41), the R_t for 'MESH' is 18.5 % higher than 'KNIT' in the sitting condition and 16.6 % and 37.6 % lower than 'KNIT' in the walking condition and running condition, respectively. This finding suggests that the effect of fabric may vary the thermal insulation property of the footwear apart from the footwear area factor. The footwear area factor can only provide an estimation of the thermal insulation property of the footwear.

E. COMPARISON WITH PREVIOUSLY REPORTED RESULTS

The results are comparable to those reported elsewhere. The air layer insulation measured in the barefoot condition in the current foot manikin is 0.099 °C · m^2/W, which falls within the range of other studies (0.090 °C · m^2/W in [34], 0.108 °C · m^2/W in [35] and 0.132 °C · m^2/W in [7]). The variation is caused by the differences in skin temperature, footwear size, shape and environmental condition.

F. REPEATABILITY OF MEASUREMENTS

The repeatability of the measurements of foot temperature and total thermal insulation have been evaluated. The results are listed in Table 7. The coefficient of variation (CV) for the skin temperature measurement is generally less than 2 %, and the CV for R_t ranges from 0.8 % to 5.3 % and is less than 4.0 %. This finding indicates that the foot manikin system is reliable.

G. VALIDATION WITH REAL HUMAN FEET

For validation, three additional participants were invited for human trials under sitting, walking and running conditions. The experimental protocol was similar to wearer trial experiment mentioned in Section II.C.1 which includes 30 min stabilization, followed by 20 min sitting + 20 min resting, 30 min walking + 30 min resting or 30 min running + 30 min resting. The sequence of sitting, walking and running is randomized. As plantar is known to be a surrogate of shear stress and skin perfusion which is often associated with the feeling of discomfort, the surface temperature on the plantar side was measured (Ports 6, 8, 9) and compared against the foot manikin results. Correlation analysis was performed for validation. The Pearson's r ranges from 0.82 to 0.87 for the sitting session, 0.59 to 0.67 for the walking session and 0.71 to 0.88 for the running session. The results suggest that the foot manikin can reflect the thermal reaction of human feet quite well.

H. LIMITATIONS OF THE DEVELOPED FOOT MANIKIN

In this study, the wind supply approach can effectively simplify the mechanical components that are required to support the motion of the foot manikin at a given speed and/or a specified activity. The corresponding foot temperature increases

TABLE 7. Repeatability of measurements on foot temperature and total thermal insulation. The coefficient of variation is calculated from three measurements.

		Port-1	Port-2	Port-3	Port-4	Port-5	Port-6	Port-7	Port-8	Port-9	Port-10	Port-11	Port-12	Port-13	Port-14	R_t
Sit	BAREFOOT	0.50	0.42	0.37	0.30	0.62	0.02	0.36	0.08	0.33	0.24	0.26	0.19	0.16	0.01	5.2
	MESH	0.29	0.42	0.29	0.16	0.22	0.18	0.22	0.34	0.06	0.12	0.18	0.11	0.01	0.05	5.1
	LEATHER	0.28	0.47	0.32	0.49	0.48	0.68	0.64	0.50	0.37	0.28	0.11	0.09	0.44	0.05	4.7
	KNIT	0.02	0.42	0.49	0.25	0.01	0.16	0.41	0.37	0.35	0.45	0.40	0.19	0.19	0.05	5.1
	CANVAS	0.32	0.22	0.21	0.06	0.43	0.42	0.44	0.23	0.44	0.01	0.11	0.48	0.44	0.03	1.5
	SLIPPER	0.60	0.79	0.55	0.53	0.28	0.53	0.56	0.52	0.36	0.46	0.27	0.14	0.11	0.02	2.1
Walk	BAREFOOT	0.55	0.32	0.08	0.21	0.06	0.33	0.13	0.42	0.45	0.47	0.27	0.24	0.33	0.31	1.0
	MESH	0.83	1.13	0.84	0.89	1.11	2.38	2.15	2.23	1.74	1.40	0.49	1.41	1.36	0.01	2.3
	LEATHER	0.42	0.25	0.16	0.11	0.53	0.51	0.50	0.40	0.55	0.25	0.15	0.21	0.22	0.01	4.1
	KNIT	0.13	0.10	0.13	0.28	0.11	0.26	0.20	0.36	0.44	0.12	0.11	0.42	0.34	0.01	3.9
	CANVAS	0.26	0.45	0.51	0.30	0.26	0.73	0.64	0.73	0.54	0.43	0.41	0.39	0.33	0.02	5.2
	SLIPPER	0.29	0.33	0.09	0.34	0.25	0.51	0.37	0.54	0.61	0.16	0.17	0.23	0.35	0.02	2.7
Run	BAREFOOT	0.06	0.01	0.13	0.13	0.00	0.04	0.27	0.06	0.16	0.25	0.16	0.10	0.21	0.19	0.8
	MESH	0.40	0.35	0.34	0.43	0.28	0.39	0.07	0.25	0.16	0.36	0.36	0.05	0.06	1.33	5.0
	LEATHER	0.20	0.39	0.34	0.17	0.06	0.29	0.30	0.21	0.41	0.19	0.22	0.03	0.21	0.01	3.5
	KNIT	0.32	0.19	0.05	0.45	0.30	0.08	0.14	0.17	0.21	0.06	0.08	0.09	0.02	0.02	2.2
	CANVAS	0.05	0.09	0.06	0.02	0.10	0.09	0.01	0.00	0.07	0.02	0.02	0.07	0.05	0.02	5.3
	SLIPPER	0.14	0.20	0.27	0.00	0.35	0.07	0.01	0.20	0.07	0.01	0.04	0.01	0.03	0.01	4.8

TABLE 8. Multiple comparison table for different footwear types.

			Average skin temp.		R_T		R_{ft}	
	(I)	(J)	Mean Difference (I-J)	Sig.	Mean Difference (I-J)	Sig.	Mean Difference (I-J)	Sig.
Sitting	MESH	LEATHER	0.379	0.001	-0.061	0.000	-0.065	0.000
		KNIT	-0.011	1.000	0.033	0.017	0.033	0.017
		CANVAS	-0.157	0.204	0.046	0.002	0.049	0.001
		SLIPPER	-1.574	0.000	-0.066	0.000	-0.065	0.000
	LEATHER	MESH	-0.379	0.001	0.061	0.000	0.065	0.000
		KNIT	-0.390	0.001	0.094	0.000	0.098	0.000
		CANVAS	-0.536	0.000	0.107	0.000	0.115	0.000
		SLIPPER	-1.953	0.000	-0.005	0.974	0.000	1.000
	KNIT	MESH	0.011	1.000	-0.033	0.017	-0.033	0.017
		LEATHER	0.390	0.001	-0.094	0.000	-0.098	0.000
		CANVAS	-0.146	0.259	0.013	0.555	0.016	0.346
		SLIPPER	-1.563	0.000	-0.099	0.000	-0.098	0.000
	CANVAS	MESH	0.157	0.204	-0.046	0.002	-0.049	0.001
		LEATHER	0.536	0.000	-0.107	0.000	-0.115	0.000
		KNIT	0.146	0.259	-0.013	0.555	-0.016	0.346
		SLIPPER	-1.417	0.000	-0.112	0.000	-0.115	0.000
	SLIPPER	MESH	1.574	0.000	0.066	0.000	0.065	0.000
		LEATHER	1.953	0.000	0.005	0.974	0.000	1.000
		KNIT	1.563	0.000	0.099	0.000	0.098	0.000
		CANVAS	1.417	0.000	0.112	0.000	0.115	0.000
Walking	MESH	LEATHER	1.453	0.000	-0.096	0.000	-0.098	0.000
		KNIT	-0.171	0.833	-0.023	0.011	-0.023	0.011
		CANVAS	1.093	0.000	-0.002	0.991	-0.001	0.999
		SLIPPER	-2.278	0.000	-0.056	0.000	-0.055	0.000
	LEATHER	MESH	-1.453	0.000	0.096	0.000	0.098	0.000
		KNIT	-1.624	0.000	0.073	0.000	0.075	0.000
		CANVAS	-0.360	0.251	0.094	0.000	0.096	0.000
		SLIPPER	-3.731	0.000	0.041	0.000	0.042	0.000
	KNIT	MESH	0.171	0.833	0.023	0.011	0.023	0.011
		LEATHER	1.624	0.000	-0.073	0.000	-0.075	0.000
		CANVAS	1.264	0.000	0.020	0.022	0.022	0.016
		SLIPPER	-2.107	0.000	-0.033	0.001	-0.032	0.001
	CANVAS	MESH	-1.093	0.000	0.002	0.991	0.001	0.999
		LEATHER	0.360	0.251	-0.094	0.000	-0.096	0.000
		KNIT	-1.264	0.000	-0.020	0.022	-0.022	0.016
		SLIPPER	-3.371	0.000	-0.053	0.000	-0.054	0.000
	SLIPPER	MESH	2.278	0.000	0.056	0.000	0.055	0.000
		LEATHER	3.731	0.000	-0.041	0.000	-0.042	0.000
		KNIT	2.107	0.000	0.033	0.001	0.032	0.001
		CANVAS	3.371	0.000	0.053	0.000	0.054	0.000
Running	MESH	LEATHER	0.596	0.000	-0.076	0.000	-0.077	0.000
		KNIT	-0.123	0.145	-0.053	0.000	-0.053	0.000
		CANVAS	0.366	0.000	-0.031	0.001	-0.030	0.001
		SLIPPER	-1.489	0.000	-0.065	0.000	-0.065	0.000
	LEATHER	MESH	-0.596	0.000	0.076	0.000	0.077	0.000
		KNIT	-0.719	0.000	0.022	0.010	0.023	0.007
		CANVAS	-0.230	0.005	0.045	0.000	0.047	0.000
		SLIPPER	-2.085	0.000	0.010	0.333	0.012	0.240
	KNIT	MESH	0.123	0.145	0.053	0.000	0.053	0.000
		LEATHER	0.719	0.000	-0.022	0.010	-0.023	0.007
		CANVAS	0.490	0.000	0.022	0.010	0.023	0.008
		SLIPPER	-1.366	0.000	-0.012	0.221	-0.012	0.238
	CANVAS	MESH	-0.366	0.000	0.031	0.001	0.030	0.001
		LEATHER	0.230	0.005	-0.045	0.000	-0.047	0.000
		KNIT	-0.490	0.000	-0.022	0.010	-0.023	0.008
		SLIPPER	-1.856	0.000	-0.034	0.000	-0.035	0.000
	SLIPPER	MESH	1.489	0.000	0.065	0.000	0.065	0.000
		LEATHER	2.085	0.000	-0.010	0.333	-0.012	0.240
		KNIT	1.366	0.000	0.012	0.221	0.012	0.238
		CANVAS	1.856	0.000	0.034	0.000	0.035	0.000

due to repetitive vertical and shear stresses in relation to the foot strike configuration and even deformation of the foot cannot be measured, which affects the outcomes and discrepancies from the real situations of shoe wearing.

This foot manikin can only measure the dry heat loss of footwear. People profusely sweat during exercising, and evaporation is another fundamental means of heat transfer. The current system cannot measure the evaporative resistance

TABLE 9. Multiple comparison table for different activity levels.

	(I)	(J)	Average skin temperature Mean Difference (I-J)	Sig.	R_t Mean Difference (I-J)	Sig.	R_{ft} Mean Difference (I-J)	Sig.
BAREFOOT	Sit	Walk	-2.787	0.000	0.067	0.000		
		Run	-3.566	0.000	0.074	0.000		
	Walk	Sit	2.787	0.000	-0.067	0.000		
		Run	-0.779	0.000	0.008	0.055		
	Run	Sit	3.566	0.000	-0.074	0.000		
		Walk	0.779	0.000	-0.008	0.055		
MESH	Sit	Walk	-3.832	0.000	0.096	0.000	0.049	0.000
		Run	-5.240	0.000	0.123	0.000	0.071	0.000
	Walk	Sit	3.832	0.000	-0.096	0.000	-0.049	0.000
		Run	-1.408	0.001	0.027	0.009	0.022	0.023
	Run	Sit	5.240	0.000	-0.123	0.000	-0.071	0.000
		Walk	1.408	0.001	-0.027	0.009	-0.022	0.023
LEATHER	Sit	Walk	-2.757	0.000	0.061	0.001	0.017	0.181
		Run	-5.023	0.000	0.109	0.000	0.059	0.001
	Walk	Sit	2.757	0.000	-0.061	0.001	-0.017	0.181
		Run	-2.266	0.000	0.048	0.003	0.043	0.005
	Run	Sit	5.023	0.000	-0.109	0.000	-0.059	0.001
		Walk	2.266	0.000	-0.048	0.003	-0.043	0.005
KNIT	Sit	Walk	-3.991	0.000	0.040	0.001	-0.007	0.437
		Run	-5.352	0.000	0.037	0.001	-0.016	0.061
	Walk	Sit	3.991	0.000	-0.040	0.001	0.007	0.437
		Run	-1.361	0.000	-0.003	0.827	-0.009	0.322
	Run	Sit	5.352	0.000	-0.037	0.001	0.016	0.061
		Walk	1.361	0.000	0.003	0.827	0.009	0.322
CANVAS	Sit	Walk	-2.581	0.000	0.048	0.000	-0.002	0.895
		Run	-4.717	0.000	0.046	0.000	-0.009	0.198
	Walk	Sit	2.581	0.000	-0.048	0.000	0.002	0.895
		Run	-2.135	0.000	-0.001	0.958	-0.007	0.345
	Run	Sit	4.717	0.000	-0.046	0.000	0.009	0.198
		Walk	2.135	0.000	0.001	0.958	0.007	0.345
SLIPPER	Sit	Walk	-4.536	0.000	0.107	0.000	0.059	0.000
		Run	-5.156	0.000	0.124	0.000	0.071	0.000
	Walk	Sit	4.536	0.000	-0.107	0.000	-0.059	0.000
		Run	-0.620	0.000	0.017	0.036	0.012	0.134
	Run	Sit	5.156	0.000	-0.124	0.000	-0.071	0.000
		Walk	0.620	0.000	-0.017	0.036	-0.012	0.134

of footwear or drying property of footwear material [36]. However, precise control of the local sweat rate of the foot manikin is challenging since the distribution of sweat glands is uneven throughout the surface of the foot. For example, the sweat secretion rate from the dorsal surface may be higher than the sweat secretion rate from the sole and plantar side of the toes [37].

Besides, ordinary heater with uniform heating element distribution was used as the guard heater. This can dramatically minimize the heat transfer between the shin and the foot; however its temperature distribution is not exactly the same as the edge of the foot manikin. Hence, we will design special heating sheet for the guard heater in the future so as to prevent any vertical heat transfer.

V. CONCLUSIONS

The developed foot manikin is a useful tool for evaluating the heat exchange between the foot and footwear in various environmental conditions. Understanding the regional distribution of skin temperature contributes to advancing footwear design. Considering cold protective footwear as an example, maintaining the skin temperature in the toe region (i.e., coolest region) is important. The general features of the developed foot manikin system include

- Length is 24 cm and the surface area is 537.5 cm^2.
- Equipped with a metatarsal phalangeal joint and an ankle joint, which enables various type of footwear to be worn onto the foot manikin.
- External layer is constructed of silicone rubber, which is as soft as human skin.
- Dorsal skin of the foot was controlled at a predetermined temperature.
- Skin temperature distribution can be adjusted by exchanging with other heating sheets.
- Skin of the foot manikin contains a zipper on the medial side of the heel, which enables the manikin to be easily pulled off the skin and facilitates changing of the heating sheet.

- Setup is simple. Only one heating sheet and one control unit is required to obtain the gradient temperature distribution.
- Guard heating sheet is attached at the shin for minimizing vertical heat flow from the foot.
- Results are repeatable.
- Affordable cost for product development

Based on the five investigated footwear, the results prove that R_t is negatively related to TD% but positively related to f_{ft}. The relationship exhibits an approximate trend for the five footwear. Further investigations of a greater variety of footwear should be considered to validate this relationship for boarder applicability.

Compared with foot manikins in which the foot is divided into several zones, the proposed foot manikin is simpler, more similar to the wear condition and can be manufactured at an acceptable cost. The instrument offers a scientific and reliable method to assess the in-shoe temperature environment for the evaluation of the thermal condition of footwear in response to the different activity levels of wearers. The findings can therefore provide insights into footwear design for various end-uses and activities that would facilitate the continuous design and development of quality footwear.

It is hoped that water supply system can be incorporated in the current setup so that the evaporation resistance of the footwear can be measured as well.

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