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Kalev Kuklane[ab], Rallema Afanasieva[c], Olga Burmistrova[c], Nina Bessonova[c] & Ingvar Holmér[a]

[a] Department of Occupational Medicine, National Institute for Working Life, Solna, Sweden

[b] Department of Human Work Sciences, Luleå University of Technology, Sweden

[c] Institute of Labour Medicine, Russian Academy of Medical Sciences, Moscow, Russia

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Kalev Kuklane

Department of Occupational Medicine,
National Institute for Working Life, Solna, Sweden
Department of Human Work Sciences,
Luleå University of Technology, Sweden

Rallema **Afanasieva**
Olga Burmistrova
Nina Bessonova

Institute of Labour Medicine,
Russian Academy of Medical Sciences, Moscow, Russia

Ingvar Holmér

Department of Occupational Medicine,
National Institute for Working Life, Solna, Sweden

This study compared the methods of determining footwear insulation on human participants and a thermal foot model. Another purpose was to find the minimal number of measurement points on the human foot that is needed for insulation calculation. A bare foot was tested at 3 ambient temperatures on 6 participants. Three types of footwear were tested on 2 participants. The mean insulation for a bare foot obtained on the participant and model were similar. The insulation of warm footwear measured by the 2 methods was also similar. For thin footwear the insulation values from the participants were higher than those from the thermal model. The differences could be related to undefined physiological factors. Two points on the foot can be enough to measure the insulation of footwear on human participants (*r* = .98). However, due to the big individual differences of humans, and good repeatability and simplicity of the thermal foot method, the latter should be preferred for testing.

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Correspondence and requests for reprints should be sent to Kalev Kuklane, Department of Occupational Medicine, National Institute for Working Life, S-171 84 Solna, Sweden. E-mail: < kkuklane@niwl.se >.

foot thermal insulation footwear thermal foot model skin temperature heat loss

1. INTRODUCTION

Complaints about cold feet during occupational and leisure-time cold exposure are well-known. Relevant information on cold protective properties can help the user in the selection of footwear. The European Standard for footwear testing (Standard No. EN 344:1992; European Committee for Standardization [CEN], 1992) and the labelling system do not require the insulation value for footwear. A sensor is fixed to the inner sole and the footwear is filled with steel balls (0 5 mm, 4 kg). The temperature change of less than 10 °C at a gradient of 40 °C (from +20 to —20 °C) is the criterion for passing the test. Thus, the test is related mainly to the sole area.

By a former Soviet Standard for footwear testing (Standard No. GOST 12.4.104-81; Standardisation Committee of the USSR, 1981) a calculation of the insulation was required. It calculated the insulation of the whole foot. Insulation calculation for separate zones (soles, toes) was not dealt with. However, that standard is not in force any more.

A method of measuring thermal insulation on a thermal foot model has been worked out (Bergquist & Holmér, 1997; Kuklane & Holmér, 1998; Santee & Endrusick, 1988). The method has been used by commercial companies and defence research establishments to test and evaluate the footwear, however, most of that information has not been published (R.A. Burke, personal communication, 1998; Uedelhoven, 1994; W.H. Uedelhoven, personal communication, 1998).

This study aimed to compare methods of determining footwear insulation on human participants and on a thermal foot model. Another purpose was to find the minimal number of measurement points on the human foot that is needed for insulation calculation.

2. METHODS

The tests were carried out on a naked foot at three environmental temperatures: 23, 18, and 13 °C. Two male and 4 female participants

(45 [30-66] years, 166 [156-173] cm, 72 [57-86] kg) participated in the study. All participants were measured at 23 °C, 4 of them at 18 °C, and 2 persons at 13 °C.

Eleven heat flow and temperature sensors, with the thickness of 3 mm and the area of 1.8 cm^2 (Standard No. GOST 12.4.185-96; Standardisation Committee of the Russian Federation, 1996), were attached to the foot (Table 1 and Figure 1). Air temperature was measured with a mercury thermometer. During the measurements on a naked foot, the leg was supported by a chair at the calf region so that the foot was hanging in

TABLE 1. Measurement Points on the Human Foot and Corresponding Zones on the Model

No.	Location on Human Foot	Zone on Model
1	Dorsal surface of first (big) toe	I—toes
2	Superior medial dorsal surface of foot	IV—mid-foot
3	Superior lateral dorsal surface of foot	IV—mid-foot
4	Middle of medial surface of foot	IV—mid-foot
5	Posterior medial dorsal surface of foot	IV—mid-foot
6	Posterior lateral dorsal surface of foot	IV—mid-foot
7	Lateral heel, behind ankle bone	III—heel; V—ankle
8	Plantar surface of first (big) toe	I—toes
9	Middle of superior sole	II—mid-sole
10	Mid-sole	II—mid-sole
11	Middle of plantar heel	III—heel

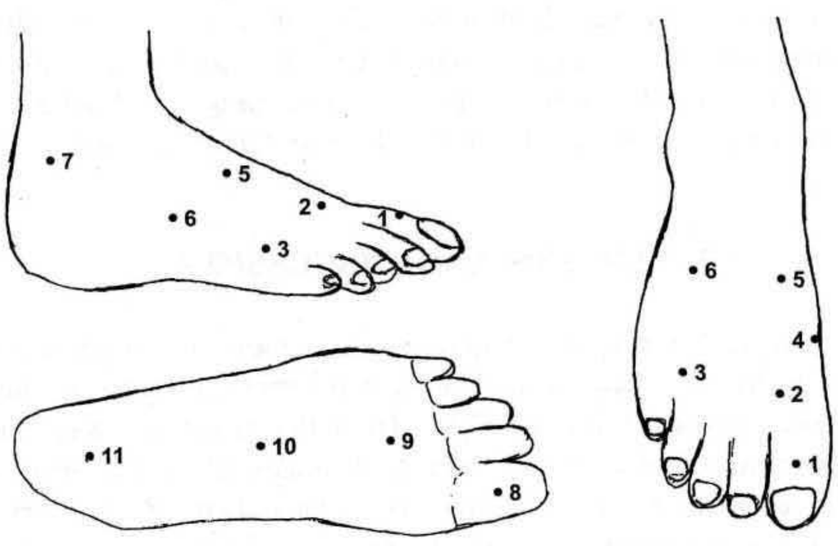

Figure 1. Measurement points on the foot according to Table 1.

the air. The participants sat in such a position for 1 hr. The general thermal sensation of the participants during the tests was around neutral at 23 and 18 °C, and somewhat cooler at 13 °C. The heat flow and temperature values were recorded every 10th min. The average of the 40th, 50th, and 60th min heat loss and the last skin temperature value were used in the insulation calculation.

Then three types of footwear were tested on two participants by the same method. WS was warm footwear for winter use, AS a leather boot without lining, and BS a rubber boot without lining. The footwear is described more precisely in previous papers (Kuklane, Geng, & Holmér, 1998; Kuklane & Holmér, 1998). One participant used footwear size 41 and the other size 43. During the tests with footwear, a thin sock, similar to the one that was donned during thermal foot model measurements, was used. The measuring procedure was the same as with a naked foot except that this time the soles were supported on the floor while the participant was seated. These tests were carried out at 13 and 19.5 °C.

Footwear size 41 was used on the model. The model and test procedure have been described previously (Kuklane & Holmér, 1998). The air layer insulation values measured on a naked foot were acquired while the model was standing upside down, that is, sole up.

The stepwise regression between the insulation of separate points and average insulation was used to find the minimal number of measuring points on a foot for insulation calculation. The point with the best correlation coefficient was checked with all others, and a pair with the best correlation was chosen to continue. This continued until the correlation coefficient did not improve considerably any further. The method was used separately for naked-foot and footwear data.

3. RESULTS AND DISCUSSION

Generally, the air layer insulation of a bare foot, measured on participants, was close to the weighted mean. The weighted mean air layer insulation for all conditions was 0.108 m^2 °C/W. The latter in its turn was similar to the value measured on the thermal foot model. The mean insulation values for each temperature differed less than 0.01 m^2 °C/W from the insulation that was measured on the thermal foot model. This makes the dry heat transfer coefficient ($h_{dry} = 1/I_{dry}$) 9.3 W/m^2 °C.

TABLE 2. Mean Heat Losses (H), Skin Temperatures (T_{sk}), and Air Layer Insulation (I_{air}) of a Naked Foot at Various Environmental Temperatures, and the Insulation That Was Derived From Model Tests

	23 °C			18 °C			13 °C			Model
Foot Zones	H (W/m²)	T_{sk} (°C)	I_{air} (m² °C/W)	H (W/m²)	T_{sk} (°C)	I_{air} (m² °C/W)	H (W/m²)	T_{sk} (°C)	I_{air} (m² °C/W)	I_{air} (m² °C/W)
I—Toes	55.8	28.3	0.098	42.4	22.9	0.107	27.9	17.6	0.164	0.098
II—Mid-Sole	47.5	27.7	0.103	58.2	23.6	0.089	71.3	21.2	0.115	0.130
III—Heel	40.8	28.7	0.144	47.2	24.7	0.134	62.1	21.4	0.136	0.115
IV—Mid-Foot	50.8	28.9	0.118	67.4	24.7	0.094	96.8	20.5	0.077	0.103
V—Ankle	30.8	29.5	0.216	43.9	25.7	0.165	62.6	22.1	0.145	0.108
Total	49.5	28.6	0.115	56.9	24.2	0.102	73.3	20.3	0.099	0.108

The insulation of various areas differed considerably (0.100-0.180 m^2 °C/W). The air layer insulation of the same location differed at different temperatures. Even the same participant at the same temperature could have these values different. This could depend on the curvature of the particular area, air streams around the foot, and how the foot was exactly located. Some effect could be related to the sensor size (0 13 mm) and its contact with skin. At the same time the values from the thermal foot model were remarkably stable. The mean heat losses from the feet, skin temperatures, and calculated air layer insulation are shown in Table 2.

The differences between participants in area insulation and in total insulation (0.082-0.167 m^2 °C/W) were substantial. The higher total insulation at 23 °C and lower at 13 °C could be related to the increased air velocity at the test location with higher cooling power and increased natural convection due to a higher temperature gradient. However, toe insulation showed an opposite effect.

Figure 2 shows the weighted average footwear and air layer insulation measured on participants and on the thermal foot model as total and for some locations. There was no significant difference in insulation values measured on humans and on the thermal foot model for the warmest footwear (WS) at 13 or 19.5 °C (Table 3) in both participants. However, for AS and BS the results of the human and foot model did differ (Figure 2 and Table 3). One participant kept relatively high foot temperature (mean 31.4 °C, toes 32.2 °C for AS and BS at 19.5 °C). For that participant the insulation values for AS and BS at 19.5 °C were very close to model values (difference < 6% for BS, < 1% for AS). At 13 °C, the insulation values measured on that participant were somewhat higher than those obtained on the model. At the same time the insulation values measured on another participant with relatively low foot skin temperatures (mean 29.0 °C, toes 27.8 °C for AS and BS at 19.5 °C) were much higher and similar to the first participant at 13 °C. The first participant showed even at 13 °C somewhat lower insulation values that were closer to the model values than the second participant at 19.5 °C. Skin temperatures of the first participant at 13 °C were somewhat higher, too (mean 29.6 °C, toes 28.7 °C for AS and BS). The biggest differences were in the footwear without warm lining showing too high insulation compared to the model results.

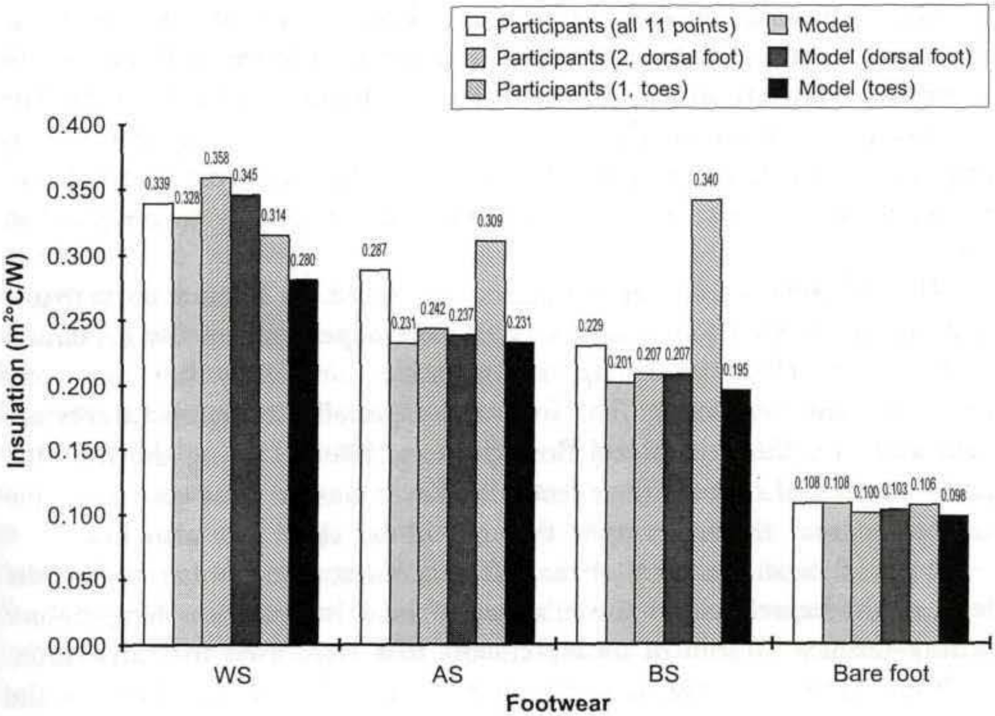

Figure 2. Insulation values from measurements on participants and on the thermal foot model. The insulation values on participants are based on all (11) points, 2 points (5 and 6) on the dorsal foot, and 1 point (1) on the big toe. *Notes.* WS—warm footwear for winter use, AS—a leather boot without lining, BS—a rubber boot without lining.

Table 3 shows the differences in insulation measured on participants and on the thermal foot model. Some differences could be related to the foot shape, its placement in a shoe, and so forth, which influence the local insulation. However, total insulation values should have been similar.

TABLE 3. Differences in Insulation (I_{total}, I_{dorsal}, I_{toe}) Measured on Humans and on the Model (%)

Boot	I_{total}	I_{dorsal}	I_{toe}
WS	2.8	4.2	10.9
AS	30.6	3.1	25.2
BS	14.6	0.1	43.1

Notes. WS—warm footwear for winter use, AS—a leather boot without lining, BS—a rubber boot without lining.

The differences seemed to be dependent on the location and the insulation. The warmest footwear had minimal differences in any conditions and relatively small differences locally (Figure 2 and Table 3). The insulation measured on the dorsal foot of human participants was in any conditions similar to the value that was obtained from thermal foot model measurements, whereas the biggest differences were observed in toes.

The differences between insulation measured on human participants and on the thermal foot model in toes were dependent on the insulation of footwear. The relationship was negative, indicating that toes were more affected by cooling. The foot and especially toe temperatures are dependent on the skin blood flow (Lotens, 1989). During the tests the participants had to keep their feet still. There was no heat generated due to motion and the heat input through blood flow was also low.

It could be suspected that the differences between human and model tests might be related to the changes of heat loss or skin temperature during the last 10 min of measurements that were used for calculation, or both. However, that was not supported by the actual data, as the changes in heat loss and skin temperature in toes were not much different from those in the dorsal foot or total. The average skin temperature did not differ between the locations more than 1.3 °C whereas the differences in heat losses did not exceed 20 W/m^2 (BS).

It could be possible that the differences between the insulation values from the human and the model tests are related to thermal balance in the whole body and in a specific body part. Previous studies also showed that insulation of a garment measured on human participants could be higher than that measured on a thermal model (Ducharme & Brooks, 1998; Ducharme, Potter, & Brooks, 1998). It was found that the insulation values measured on the participants were close to those measured on the model when the participants were at thermal comfort.

Depending on body shape (curvature) the question of the contact between sensors and human skin could be raised. The extremities have relatively small radiuses so the contact between the toes and heat flow sensor could be worse than in other parts of the foot. Simultaneously, the small areas could gain a certain insulation from the sensor itself and the tape. However, this does not explain the differences that occur during measurements at different ambient temperatures.

Another source for differences between the human and model tests could be sweat secretion and evaporation. Sweat evaporation could reduce the skin temperature without the heat flux transducers registering the increased heat flow. However, sweating is usually activated at high temperatures. It is questionable if sweating had a considerable effect under measuring conditions in this study—muscle activity was low and thus sweating rate was probably low. Another question could be how excited or irritated the participants were. Excitement can increase sweating even without physical activity. This "cold sweat" could have a similar effect on thermal state as sweating due to high physical activity. The participants of this study had taken part in various tests before, were familiarised with the procedure, so excitement should not have been the reason for profuse sweating. However, the evaporation of sweat would be less at lower skin and ambient temperatures. This could cause the moisture stay on the skin surface. At the same time there could not be any evaporation through the sensor. In that case the conductivity of the skin could play a role by removing heat from under the sensor towards surrounding areas, where it can be easier removed by convection or evaporation. The sweat layer between the sensor and skin could make the heat transfer easier. The similar air layer insulation values on various parts of the foot measured on a bare foot seemed to support this line of thought. Most sweat evaporated in the open air and did not build a conducting layer on the foot surface, as it happened inside the footwear. The exception from this pattern was the air layer insulation of the toes. This could be explained by the much higher difference of the toe skin temperature compared to the other areas (Table 2). Although the sweating is present at comfort temperatures, the temperature differences are usually very small between various areas, reducing the effect of conductivity.

One more speculation could be made. Low physical activity (immobility) did not enhance pumping blood to feet and especially to the skin. Further, the heat losses were not any more directly connected to the blood flow to the skin, but to slow heat losses from the foot core. Although the temperature changed slowly, the heat flow diminished considerably. This could refer to the different characteristics of heat loss and skin temperature change during cooling. The effect could also be connected with concurrent heat exchange during cooling.

If any of these reasons were true, then the curve of clothing insulation measured on humans at various environmental conditions (cold—comfort—heat) should be parabola-like with its lowest point at comfort that will be equal to measurements on a manikin. However, those changes of insulation values measured on humans would not be related to clothing properties, including actual insulation, but to the physiological reaction.

If the effect of personal protective equipment is studied on separate parts of a human body, then there can be a risk of strongly overestimating the insulation of those particular zones that feel thermally most uncomfortable, that is, do cool most. Considering that the insulation value is a physical variable, it seems that it can be easier measured on a manikin according to a standard method. Further estimations and calculations or simulations could be made for a particular condition. For that particular condition insulation should be a constant. During human tests there are too many unknown factors involved. However, these factors should be taken into account during further modelling or any other estimations that are connected with humans.

Standard GOST 12.4.185-96 (Standardisation Committee of the Russian Federation, 1996) requires measuring garment insulation on participants who are at thermal comfort. At the same time there should be a certain gradient available between skin and ambient temperatures. These requirements are possible to follow as the measurement locations are not affected by cooling as easily as the extremities. During the insulation measurements of the extremities, for example, feet, the cooling continues due to various factors including immobility, reduction of blood flow, and so forth, and the temperature gradient can be reduced to very low levels increasing the error. The footwear insulation measurements can be then recommended to be carried out based on a few measuring points that are less affected by cooling, for example, points 5 and 6 on the dorsal foot (Table 1 and Figures 1 and 2). However, the insulation measured there will be strongly related to the local insulation that does not certainly reflect the total insulation.

On the basis of the results from different trials with 11 sensors, a minimal number and location of points that are needed for foot insulation determination on human participants were chosen. By the results of analysis, the number of points could be 2-4. However, even 2 points could give good enough correlation and adding more points would not improve the accuracy. For the measurements of footwear the points should be located at points 3 and 4 (r = 98.2%; Table 1 and Figure 1). The set of 4 points had correlation of 99.3% (points 2, 3, 4, and 7; Table 1 and Figure 1). For the bare foot measurements the points were somewhat different: r = 97.5% for points 2 and 6, and *r* = 98.5% for points 2, 5, 6, and 7. The points could be useful for further studies on the footwear whereas the number and location could be critical for some tests, for example, walking, because of technical and comfort reasons.

During the tests an extra measurement was carried out. In that test the participant with a foot size 43 tried the boot WS size 41. The insulation reduced more than 17% while using the smaller size.

4. CONCLUSIONS

- The tests on the human foot and on the thermal foot model gave similar results in terms of total insulation.
- The variation of the local insulation values is most likely dependent on foot shape and its location in the footwear.
- The cooling of the participant is probably the reason why the measured insulation values from participants were higher than those measured on the thermal model. The effect was bigger in boots with low insulation and at extreme points of the foot, especially in toes.
- It can be suggested to use the thermal foot method as a standard method for footwear thermal testing rather than tests on participants.
- The recommended minimal number of measuring points on the human foot for footwear insulation determination is 2 and they should be preferably located at the superior lateral dorsal surface of the foot and in the middle of the medial surface of the foot.
- Further studies are needed to explain the reasons for the differences in insulation measurements on humans at various temperatures.

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