Interlaboratory tests on thermal foot models

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Contents

Introduction

There have been carried out several interlaboratory tests on thermal manikins in order to validate test methods. Round Robin tests have been carried out on ordinary manikins (Anttonen, 2000) and sweating manikins (McCullough et al., 2002). Standard tests have been evaluated or proposed based on several joint studies, e.g. protective clothes against cold (ENV 342, 2001; Meinander et al., 2001) and vehicle climate (Nilsson, 2000). However, there is much less information available on joint studies of for example footwear testing.

Sources for possible variances in insulation values can be found in different measurement set-ups, foot model design and test conditions. In order to compare measurements in different laboratories and with different models and measuring principles a limited Round Robin test was designed.

The Climate research group at the National Institute for Working Life (NIWL) administered the work and co-ordination. Arbesko AB and Sweden Boots AB supplied the footwear. All participating laboratories did the tests at their own cost.

Table 1. *Information on foot models of institutes that have carried out the tests. MTNW – Measurement Technology NW, USA; NIWL - National Institute for Working Life, Sweden (project co-ordinator); ORIOH - Oulu Regional Institute of Occupational Health, Finland; QRI - Quartermasters Research Institute, China; USARIEM - US Army Research Institute of Environmental Medicine, USA; VTT - Technical Research Centre of Finland, Finland; WIWEB - Bundeswehr Institute for Materials, Explosives, Fuels and Lubricants, Germany.*

	MTNW	NIWL	ORIOH	QRI	USARIEM	VTT	WIWEB
Shell	Copper	Plastic	Alum.	Alum.	Copper	Plastic	
Side	Left	Left	Right	Right	Right	Left	Right
No. of zones	17	8		12	30	9	
Use of weight		Possible	Possible		Not available	Not available	
Movement		Pneumatic			Not available	Not available	
Sweating mechanism	Volumetric delivery to porous metal skin surface	Peristaltic pump, moisture distribution within sock		Peristaltic pump	Not available	Water supply to under the "skin" where it evaporates through membrane	
Water supply	Liquid	Liquid	Liquid	Liquid	No	Vapour	
No. of glands	Porous surf.	5		8	None	24	
Weight (g)		1631		5500	5360	2610	
Model height (mm)	192	410		410	395	440	
Foot length (mm)	264	254	256	257	265	264	275
Foot width (mm)		86	78	92	101	97	100
Foot height (mm)		71			66		
Foot circumf. at widest place (mm)		220			210	233	
Circumf. over heel and dorsal foot (mm)		310			325	361	
Min circumf. (leg, mm)		231		262	221	235	
Max circumf. (leg, mm)		357		392	309	377	
A_S (foot&ankle, cm^2)	912.4	653.7		577.0	1009.2 (total)	820.0	
Used size boot 2	42	41	41	42	43	43	44
Used size boot 3	41	41	41	41	42	42	44

Seven laboratories participated in the test with their thermal foot model (Table 1). SATRA (UK) did the tests according to EN 344 (1999). Foot model sizes from 254 mm to 275 mm, test boot sizes from 41 to 44, and several model construction types were represented in the study. More detailed description of several models or working principles can be found in the literature (Burke, 1999; Endrusick et al., 1992; Kurz et al., 2001; Meinander, 2000; Shen & Jiang, 2001). Several other laboratories (6) showed interest but were not able to do the testing at present.

The main output of the study is the report, which in the first instance will be used for development work on methods for determination of thermal properties of footwear and standardisation. The test series form a good basis for applying for a project further on, as well as, for suggesting changes in existing European standard (EN 344, 1999) or proposing a new (international) standard on footwear thermal testing.

Methods

A database was created for study results, thus making it possible to add test results from other test laboratories and on other footwear later on.

The test series were carried out under standardised conditions in each laboratory. In the database the equations for insulation calculations were given. Any alternative calculation methods could be included in the database if suggested by participants. Participants carried out a maximum of 10 double determinations per institution (á 90-120 minutes).

Combined measurements were made on bare foot (air layer insulation), a thin sock, a rubber boot and a winter boot. The sock and the footwear are described in Table 2. f_{cl} values were estimated by area calculation based on circumferences.

Table 2. *Sock and footwear.*

Manufacturer	Model No./Name	Weight (size 41, g)	Test code	Color	Steel rein-forcments	Sole material	Uppers	Lining	f_{cl}
	No footwear		0						
	Only sock	20	1	white		70 % cotton, 30 % polyamid			1.02
Sweden Boots AB		1010	2	Black	Steel toe	Rubber	Rubber		1.57
Arbesko Gruppen AB	520, Woodman	812	3	Black/ green	Steel toe	Nitrilrubber, felt insoles	Impregna-ted leather	Thinsulate, nylon fur	1.70

The boots were tested in conditions where sole compression and moisture effects were combined (no weight, no sweating, weight 35 kg, sweating 5 g/h). The participants were asked to carry out as many tests as they were able to.

Tests on bare foot and sock were recommended to be carried out within any temperature between +15 … +20 °C and 50 % RH. The tests on boots were recommended to be carried out at about +5 °C (±<0.5 °C) and 85±5 % RH and air velocity was recommended to be kept low (<0.5 m/s). If something in test conditions had to be changed the participants had to make a note on that in the database.

The unit m^2°C/W is used for insulation. Total insulation was calculated according to the following formula:

$$I_{t,r} = \frac{\overline{T}_s - T_a}{\sum P_i / \sum A_i}$$

where P_i - power to each zone, A_i - area of each zone; `T_s - mean surface temperature; T_a - ambient air temperature.

Results and discussion

According to standard tests (EN 344, cold insulation of sole complex) carried out at SATRA both footwear passed the test for cold protective footwear. Temperature drop in boot 2 (rubber boot) was 8.7 °C and in boot 3 (winter boot) 6.9 °C. This fits with earlier results (Kuklane et al., 1999a).

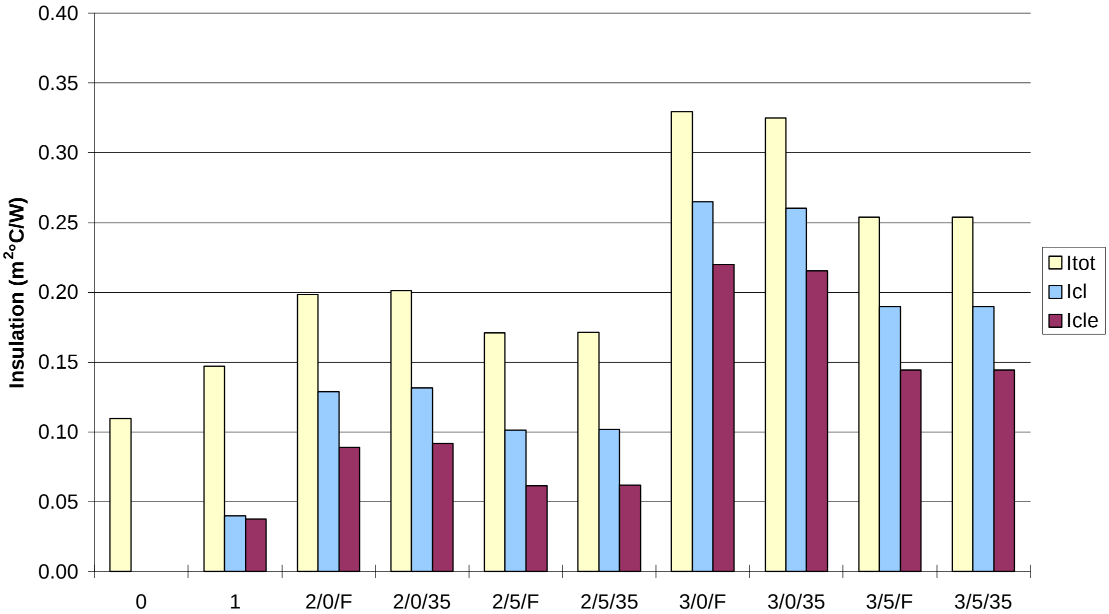

Figure 1. *Comparison of f_{cl} used in all recommended conditions (one partner). Coding: 0, 1, 2 alt. 3 – bare foot, sock, rubber boot alt. winter boot; 0 alt. 5 - dry alt. wet test (5 g/h); F alt. 35 - foot weight only alt. 35 kg load.*

Only one partner was able to carry out all recommended tests. Figure 1 shows comparison of clothing area factor (f_{cl}) used in all these conditions. Other partners skipped the tests with weight, thus in following figures these values from one partner only are not included.

The effect of f_{cl} is clearly significant for footwear testing. However, considering practical use of measured values, especially, calculation of total resultant insulation ($I_{tot,r}$) for different usage conditions, e.g. motion and wind, then intrinsic insulation ($I_{cl} = I_{tot} – I_a / f_{cl}$) and f_{cl} is not needed. On the other hand, air layer insulation (I_a) is a typical characteristic of a model and calculating effective insulation ($I_{cle} = I_{tot} – I_a$) reduces the differences between insulation values acquired with various models in different labs. Therefore, the question of I_{cl} calculation and f_{cl} use should be discussed further. Also, more information is needed to find out if f_{cl} is useful in the additive method (ISO 9920, 1993, McCullough et al., 1985) for footwear insulation calculation. Combination of footwear type, sock layers, size, insulation compression etc. does not always lead to similar increase in footwear insulation (Kuklane et al., 2000a) as it does in the case of relatively light clothing described in ISO 9920.

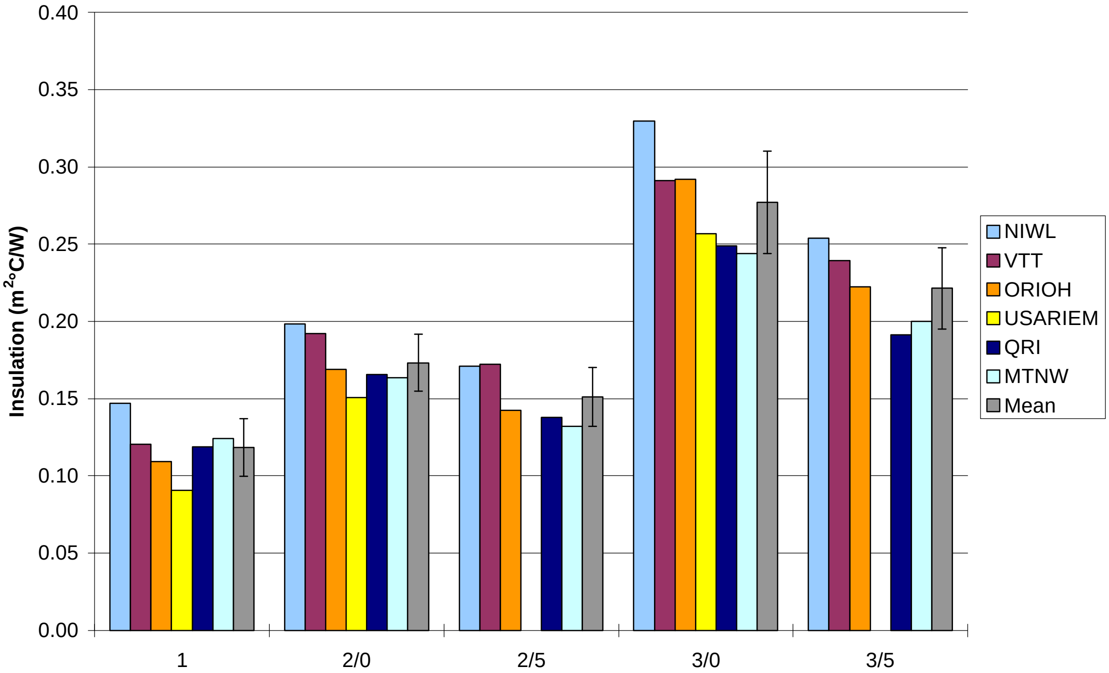

Figure 2. *Total insulation of sock, rubber and winter boot. Coding: 1, 2 alt. 3 - sock, rubber boot alt. winter boot; 0 alt. 5 - dry alt. wet test (5 g/h). USARIEM did testing at air velocity of 2 m/s.*

I_{tot} values are shown in Figure 2. In the warmest footwear the insulation differed up to 0.08 m^2°C/W (>32 %) between the lowest and highest measured values. The differences depend obviously on air movement in the chambers. USARIEM did the tests at 2 m/s wind. However, QRI and MTNW showed also relatively low I_{tot} values, but high air velocity was not reported there. The highest I_{tot} values were reported by NIWL, but they reported also one of the highest I_a (Figure 3). As discussed above, the air layer insulation of foot models is an important parameter to look for comparison of models, but also for I_{cl} and I_{cle} calculation.

The differences in air layer insulation measurements could be related to air velocity in the chamber (see USARIEM in Figure 3), model construction, e.g. type and location of surface temperature sensors (spot versus distributed sensors; sensors on the surface versus embedded into the surface), surface finish etc. These differences should be accounted for and checked in the next study.

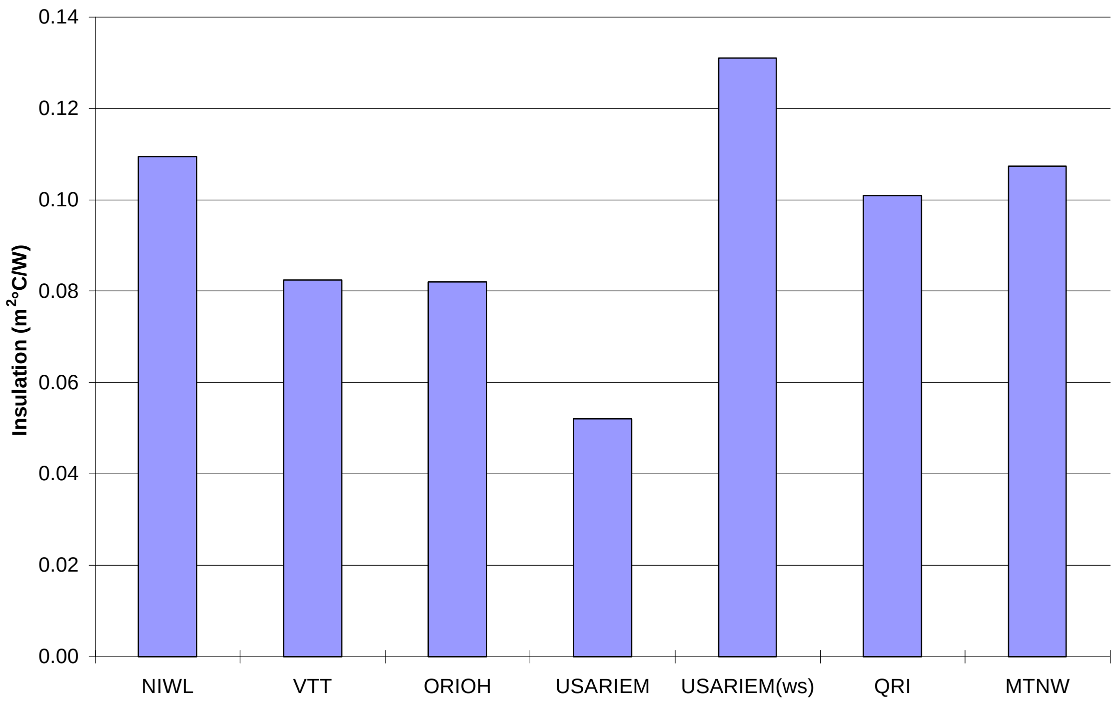

Figure 3. *Air layer insulation measured on bare foot. Tests at USARIEM were carried out with 2 m/s air velocity, USARIEM(ws) is an air layer insulation measured in wind still conditions.*

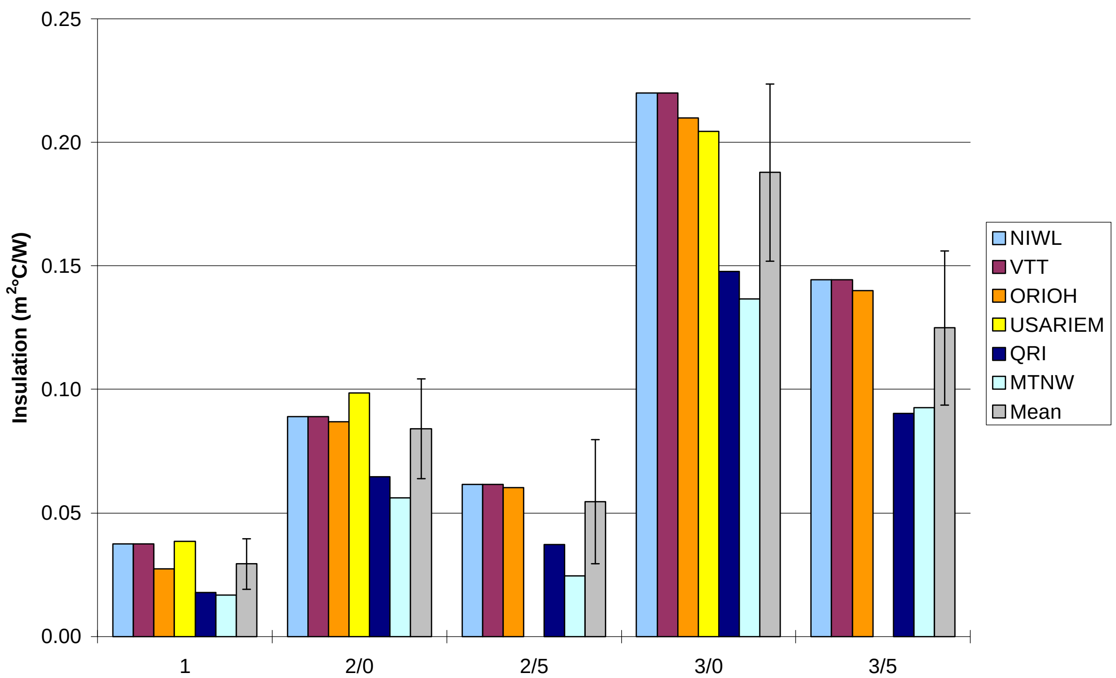

Figure 4. *Effective insulation of sock, rubber and winter boot. Coding: 1, 2 alt. 3 - sock, rubber boot alt. winter boot; 0 alt. 5 - dry alt. wet test (5 g/h).*

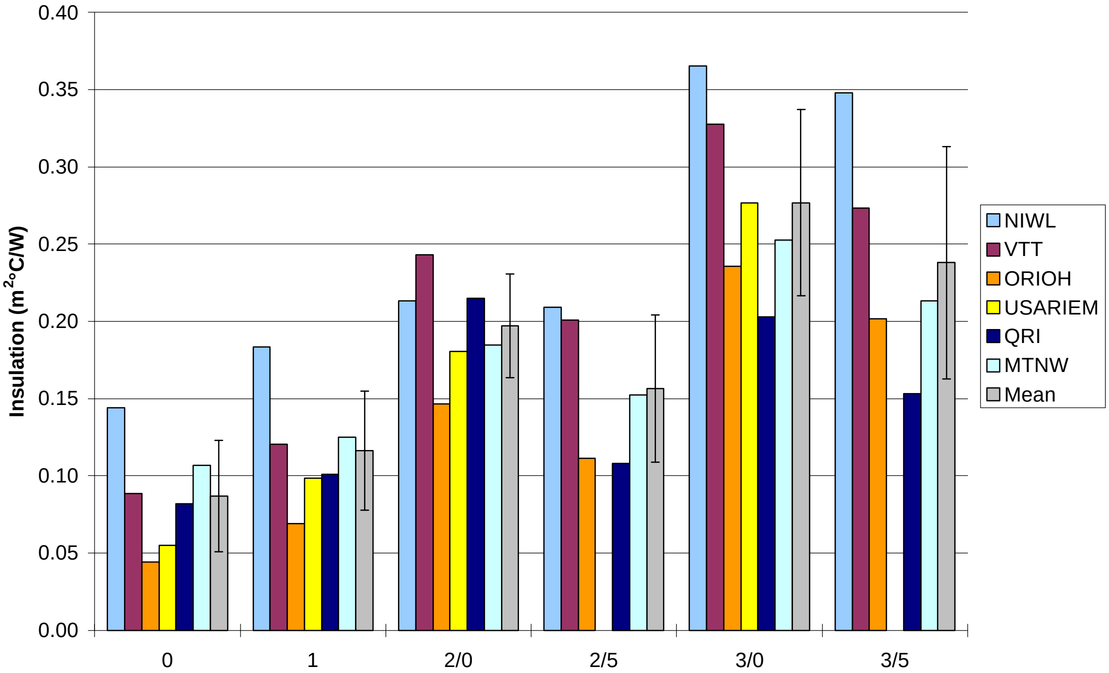

Figure 5. *Total insulation of sole zone. Coding: 0, 1, 2 alt. 3 - bare foot, sock, rubber boot alt. winter boot; 0 alt. 5 - dry alt. wet test (5 g/h).*

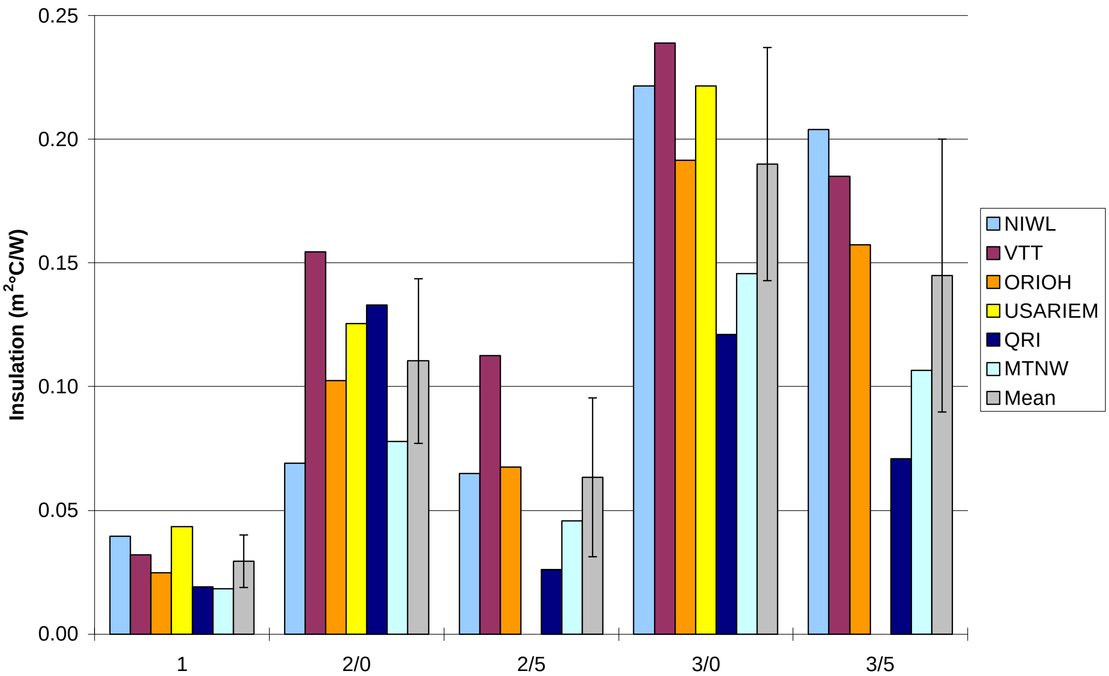

Figure 6. *Effective insulation of sole. Coding: 1, 2 alt. 3 - sock, rubber boot alt. winter boot; 0 alt. 5 - dry alt. wet test (5 g/h).*

Figure 4 shows effective insulation. It can be seen that test results are relatively similar within two groups of participants. QRI and MTNW had relatively high I_a compared to measured I_{tot}. However, this difference is present for all tested conditions. For both groups separately the mean difference for all conditions was 10 % (from 5 to 17 %), and for dry tests only it was always under 10 %. This is a good result, however, it must be investigated further what can be the source of differences between groups.

Insulation of various zones could differ more as they were not identical and did not cover always the same area. It was especially true for sole zones (Figure 5). The differences in sole insulation were less when basic insulation values were compared (Figure 6). The insulation values from QRI and MTNW were the lowest. The differences between models were over 20 %.

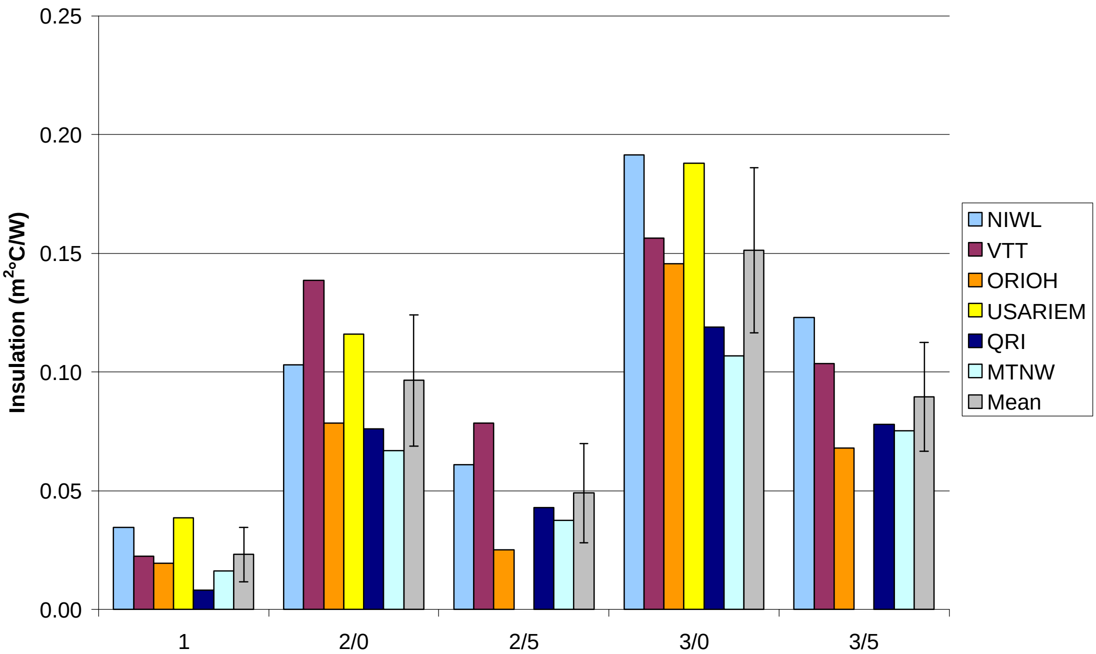

Figure 7. *Effective insulation of toes. Coding: 1, 2 alt. 3 - sock, rubber boot alt. winter boot; 0 alt. 5 - dry alt. wet test (5 g/h).*

In toe areas the insulation values had similar distribution as in the whole footwear. Effective insulation values of the toes are shown in Figure 7. The differences were relatively big. Some differences could be related to boot sizes, although, all participants ordered the boots that should fit well without a risk of damage to foot model when donning (the boots could be slightly bigger than perfect fit). In a following study several sizes should be tested on each model in order to determine the effect of footwear size for test results. For standard use it can be useful to determine the location of the most important foot zones.

Figure 8 shows how the microclimate of footwear changes during the use (results from WIWEB). This foot model evaluates wearing comfort of footwear based on the microclimate in it. This foot model works principally different from other models. However, an idea of the test series was to gather interested partners and different ideas in order to start a process of improving an old or creating a new standard for footwear thermal testing. The results from WIWEB explain behaviour of the footwear during the wet tests, and also the results that have been reported in earlier studies with the same footwear (Kuklane et al., 1999b, Kuklane et al., 2000b).

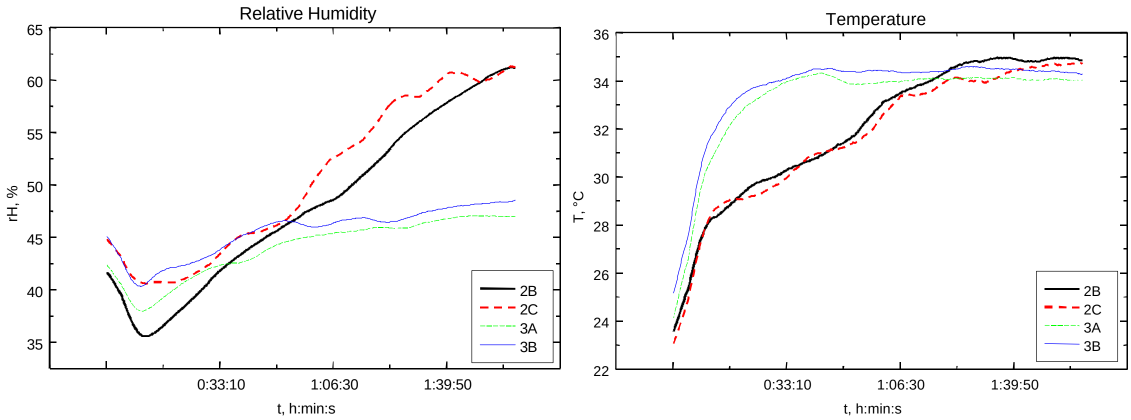

Figure 8. *Change in footwear microclimate. Coding: 2 alt. 3 - rubber boot alt. winter boot; A, B alt. C - individual tests.*

Based on the wet tests the reduction of insulation could be observed. Wet tests gave the information on evaporation quantity. However, in most cases it was not possible to calculate evaporative resistance due to lack of data on footwear microclimate humidity and temperature, and surface wetness. Only in the case of VTT, where all supplied moisture was evaporating, the calculations gave reasonable results.

Even with VTT's foot model it is important to know microclimate humidity in order to calculate the actual water vapour pressure at the skin. The average water vapour pressure at the skin depends strongly on the sweating rate and the footwear to be tested. With low sweating rate and permeable sock/footwear, the water vapour cannot spread evenly on the surface and the average water vapour pressure is much lower than the saturated vapour pressure. The assumption of 100 % relative humidity may then be overestimated. The footwear in the project was rather impermeable. However, sweating rate was rather low, and thus it could happen that the saturation point was not reached on the whole skin area.

If footwear microclimate data from WIWEB tests (Figure 8) was combined with wet test data from other models then the calculated evaporative resistance became more reasonable. Also, the use of microclimate temperature could improve the results.

Considering standardisation work in the future, information from available manikin and body part standards, e.g. ENV 342 (2001) and EN 511 (1993), is useful. Standard development should also keep in mind to improve user friendliness of information on manufacturers labels (Mäkinen et al., 2001). Similar recommendations as used for the IREQ-index (ISO/CD-11079, 2001) should be provided also for footwear (Kuklane, 1999).

Information on other types of models than used in the study could help, as well (Hering et al., 2001; Heus et al., 2002; Warmé-Janville et al., 2001).

Conclusions

Fourteen (14) institutes were interested in the study. Eight (8) of them did carry out the tests and sent in data. A database was created to compare different foot models.

Relatively big inter-laboratory differences in measuring results were obtained. The differences were smaller for total insulation values but could be more than 30 % locally. The differences can mostly be explained by differences in testing environment, different model construction and division into measuring zones, and calculation schemes (including input data) in data acquisition programmes.

More elaborate comparative tests under different conditions and with more types of footwear need to be done. The effects of differences in model construction etc. should be analysed further. For standard use it is important to determine which zones should be included in total insulation calculation and which zones should be reported separately, e.g. sole area. Foot construction and fit is an important issue and should be addressed future studies.

The conditions, measurements and calculations for wet tests should be defined.

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Summary

A limited Round Robin test has been carried out with different types of foot models. Eight laboratories were able to carry out tests. The foot models varied in sizes from 254 mm to 275 mm, representing boot sizes from 41 to 44. Six other laboratories were interested but were not able to carry out the tests within this study. A database has been created. New test results from other test laboratories and on other footwear can be added later on. The test series were carried out under standardised conditions in each laboratory. Ten (10) test conditions were recommended. All conditions had to be tested twice. Tests with bare foot and sock were carried out at about +20 °C and 50 % RH. The boots, a thin rubber and a winter boot, were tested at about +5 °C and 85 % RH. The conditioning was done at 20±2 °C and 35±5 % RH. Air velocity was kept low (<0.3 m/s). Wet tests included simulation of sweating by supplying water to the foot skin at a rate of 5 g/h/foot. Generally, 6 conditions were tested at most laboratories. The test series can be used as a basis for applying for a project further on that eventually would aim to suggest changes in existing European standard (EN 344) or propose a new (international) standard on footwear thermal testing.

Relatively big inter-laboratory differences in measuring results were obtained. The differences were smaller for total insulation values but could be more than 30 % for local zones. Most of the differences would be explained by climatic conditions, construction of foot, measuring principle a.o. More elaborate comparative tests under different conditions and with more types of footwear need to be done. The effects of differences in model construction etc. should be analysed further. For standard use it is important to determine which zones should be included in the total insulation calculation and which zones should be reported separately, e.g. sole area. The foot construction, the conditions, measurements and calculations for wet tests should be more clearly defined.

Keywords

Insulation, moisture transport, moisture absorption, thermal foot model, standard test method, footwear, cold protection, sweating simulation

Sammanfattning

Jämförande mätningar med olika typer av fotmodeller har genomförts. Åtta olika laboratorier deltog. Storleken på de olika modellerna motsvarade skostorlekar från 41 till 44. Sex andra laboratorier var intresserade att deltaga men kunde inte genomföra mätningar vid tillfället. En databas skapades som gör det möjligt att fortlöpande tillföra resultat från mätningar med typer av andra skodon samt vid andra laboratorier. Mätserien utfördes enligt standardiserade betingelser vid varje laboratorium. 10 betingelser rekommenderades. Alla betingelser skulle testas 2 gånger. Tester med naken fot och med socka gjordes vid ca +20 °C och 50 % relativ fuktighet (RF). En tunn gummistövel och en vinter stövel testades vid ca +5 °C och 85 % RF. Stövlar och sockor konditionerades vid 20±2 °C och 35±5 % RF innan testningen. Lufthastighet hölls vid låg nivå (<0.3 m/s). Våta tester inkluderade simulering av svettning med tillförsel av vatten till fotytan med 5 g/timme/foot. Vanligen testades 6 betingelser vid deltagande laboratorier. Studien kan användas som grund för att designa ett nytt projekt med målet att ta fram underlag för förslag till ändringar av nyvarande europeisk standard (EN 344) alternativt föreslå en ny (internationell) standard för testning av termiska egenskaper hos skyddsskor mot kyla och värme.

Relativt stora skillnader förelåg i mätresultat från de olika laboratorierna. Skillnaden var mindre i isolationsvärden för hela stöveln medan skillnaden överskred 30 % på lokala zoner. Skillnaderna kan förklaras bland annat med olika klimatbetingelser, fotens konstruktion och mätprincip. Mer jämförande tester under olika betingelser samt på olika skodon behöver utföras. Påverkan av modellkonstruktion osv. måste analyseras vidare. För definition av ett standardtest måste bestämmas vilka zoner som ska ingå i beräkningen av hela skons isolation och vilka zoner som ska rapporteras separat, t.ex. sulan. Fotens form och antalet zoner, testbetingelser, mätningar och beräkningar i samband med våta tester behöver bestämmas i det nya projektet..

Nyckelord

Isolation, fukttransport, fuktabsorption, mätmetod, termisk fotmodell, standard testmetod, skor, skydd mot kyla, simulering av svettning.

Annex A. Foot model at NIWL

The foot model (Figure A1) is divided into 8 zones. The model has 2 flexible joints: in ankle (border of ankle zone with mid-foot and heel zones) and at toes (border of toe zone with mid-foot and sole zones). Measuring setup with weight is shown in Figure A2.

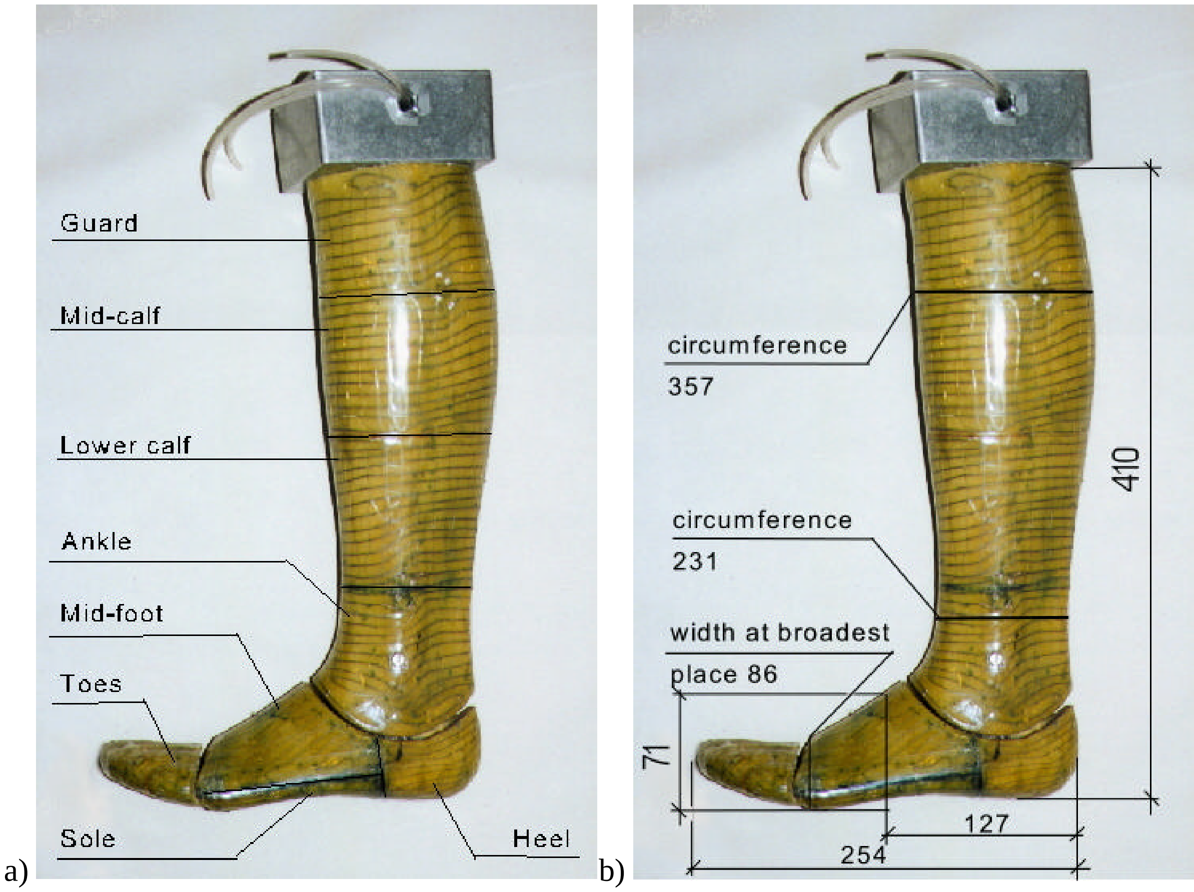

Figure A1. *The a) zones and b) dimensions (mm) of a foot model.*

The model has 3 built-in “sweat glands”: one on top of the toe zone, a second under the sole at the border of heel and sole zones, and a third on the medial side of the ankle zone. If needed, some “glands” can be added, for example, as PVC tubing onto the surface. Sweating is described more precisely in Table A1.

Surface temperature and electric power to each zone is controlled separately with a regulation computer. The European Standards regarding the insulation measurements on thermal models (EN-511, 1993; ENV-342, 1997) recommend to keep surface temperature at 30-35 °C. According to the recommendation the surface temperature of the foot model is commonly kept at 34 °C. Power input to one zone that limits temperature gradient is 300 W/m^2 (at voltage of 9 V, other zones have higher maximum power input).

The power to the foot and the heat losses are directly related (Equation A1). The program records the heat losses from each zone. Knowing heat losses, zone areas, and surface and ambient air temperatures it is possible to calculate insulation values for each zone (Equation A2) or zone groups (Equation A3). Figure A3 shows an example of test protocol together with all zone areas.

$$Q_i = \frac{P_i}{A_i} \quad \text{(A1)}$$

$$I_{Tr,i} = \frac{T_i - T_a}{Q_i} \quad \text{(A2)}$$

$$I_{Tr} = \frac{(\overline{T}_s - T_a) \cdot \sum A_i}{\sum P_i} \quad \text{(A3)}$$

Q_i - heat losses from each zone (W/m^2);
P_i - power to each zone (W);
A_i - area of each zone (m^2);
T_i - surface temperature of a zone (°C);
$\overline{T}_s$ - mean surface temperature (°C);
T_a - ambient air temperature (°C);
$I_{Tr,i}$ - thermal insulation of a zone (m^2°C/W);
I_{Tr} - resultant thermal insulation of footwear or zone group (m^2°C/W).

Figure A2. *Measuring setup with weight.*

Table A1. *Sweating principle of a thermal foot model.*

Model	Sweating description
F3	Water is supplied with a peristaltic pump (Gilson Minipuls, flow rates from 0.05 ml/min to 40 ml/min) and distributed over the foot surface in liquid form by a thin sock (20 g, 70 % cotton, 30 % polyamid). The pump is calibrated to supply specific amount of water. Equal amount of water is distributed to each “gland”. The PVC tubes for water supply from pump to the model are heated (similar to foot surface temperature) and insulated. The weight of the footwear and the sock is measured at the beginning and end of each test to record the evaporation. The length of each wet test has been kept at exactly 90 minutes to guarantee the equal total water supply in each test. The second test is carried out when the footwear has dried to the initial weight. 8 hour or longer tests have been carried out, too.

Size 40 (Swedish size) gives proper fit, but size 41 is usually used for testing because of donning reasons, especially in boots with high upper and no zipper. Also, US size 7 has been used for testing.

References

EN-511. (1993). *Protective gloves against cold* [European Standard]. Brussells: Comité Européen de Normalisation.

ENV-342. (1997). *Protective clothing against cold* [European Standard]. Brussells: Comité Européen de Normalisation.

A Provningsrapport/ Test Report

Provningslaboratorium/Testing laboratory:
Lung- och klimatprogrammet
Program for Respiratory Health and Climate
S-112 79 STOCKHOLM, SWEDEN

Datum/Date: 991026

Sida / Side: 1(1)

Rapport/ Report: F3-AsSW5a

Uppdragsgivare/Client: Internal

Nummer/ Number	Färg/ Colour	Tillverkare/ Manufacturer	Beskrivning/ Description	Vikt/Weight, g	Storlek/ Size
533	Black	Arbesko AB, Stålex, Sweden	Leather	753	41

Condition description	Standing, weight 35 kg, sock (thin, white, 70% cotton, 30% polyamid, 20 g), sweating (5 g/h)

	Toes	M.Sole	Heel	M.Foot	Ankle
Area	0.01215	0.00948	0.01022	0.01321	0.02032
Watt/m2	180	132	182	134	179
SD Watt/m2	7	2	6	9	11
Watt	2.18	1.25	1.86	1.77	3.63
Temp °C	34.1	34.0	34.0	34.1	34.0
SD HTemp	0.1	0.0	0.1	0.2	0.2
m2°C/W	0.176	0.239	0.173	0.235	0.176
clo	1.13	1.54	1.12	1.52	1.14

	L.Calf	M.Calf	Guard	Sole and Heel	Toes, Sole & Heel
Area	0.02592	0.03009	0.02656	0.01970	0.03184
Watt/m2	123	96	87	158	166
SD Watt/m2	6	7	10		
Watt	3.19	2.89	2.32	3.11	5.29
Temp °C	34.1	34.1	33.9	34.1	34.0
SD HTemp	0.1	0.2	0.2		
m2°C/W	0.256	0.329	0.359	0.200	0.190
clo	1.65	2.12	2.32	1.29	1.22

	Foot zones	Foot zones & Ankle	Toes to L.Calf	Sweat	Air
Area	0.04505	0.06537	0.09128	0.04580	
Watt/m2	157	164	152	117	
Watt	7.06	10.69	13.88	5.37	
Temp °C	34.0	34.0	34.0	34.0	2.5
SD HTemp				0.1	0.3
m2°C/W	0.201	0.193	0.207		
clo	1.30	1.24	1.34		

Saved as: C:\MODEL\f3\f3SW5ASa.TAB	User: KK
Started: 10/12 1998 14:33	
Area	**0.091**
Watt/m2	**152**
Watt	**13.9**
Foot temp °C	**34.0**
m2°C/W	**0.207**
clo	**1.34**

Termisk isolering/ Thermal insulation		Klass/ Class	Anmärkning/
m2°C/W	clo		Remark
0.207	1.34		89.83 to 90.00

Ovan angivna provningsresultat gäller endast det provade förmålet.
/ The above mentioned test result applies only to the tested sample.

Denna provningsrapport får inte återges annant än efter skriftligt tillstånd från provningslaboratoriet. / This test report must not be referred to without written permission from the testing laboratory.

Håkan Nilsson 93 - 94
modif. by Kalev Kuklane 96

Titel-Namn/Title-Name:....... Doktorand - Kalev Kuklane ....

Figure A3. *Test report sheet.*

Annex B. Foot model at USARIEM

Background

Two recently retired members of the USARIEM research staff designed the current foot models in 1976: Mr. John Breckenridge (Research Physicist) and Mr. Lee Stroschein (Mathematician). USARIEM decided to have the actual construction of the models done under contract with the University of Utah Biomedical Test Laboratory. The models were completed and delivered to USARIEM in 1977.

These new foot models replaced one that was built by the General Electric Co. in 1962. USARIEM has a collection of several older foot models, which were first used by the U.S. Army for military footwear research starting in 1943.

All of the foot models used by the U.S. Army have been constructed of copper. They were used exclusively to evaluate military, prototype, and commercial footwear for their dry thermal resistance values. None of the foot models have the ability to truly simulate human sweating at the foot surface, although evaluation of the degradation of insulation as a result of wet socks and wet footwear is done routinely. "Sweat" could be introduced to the surface of the foot model to be distributed by a thin sock but the foot model needs protection from actual water contact. For this purpose an additional thin waterproof stocking has been used.

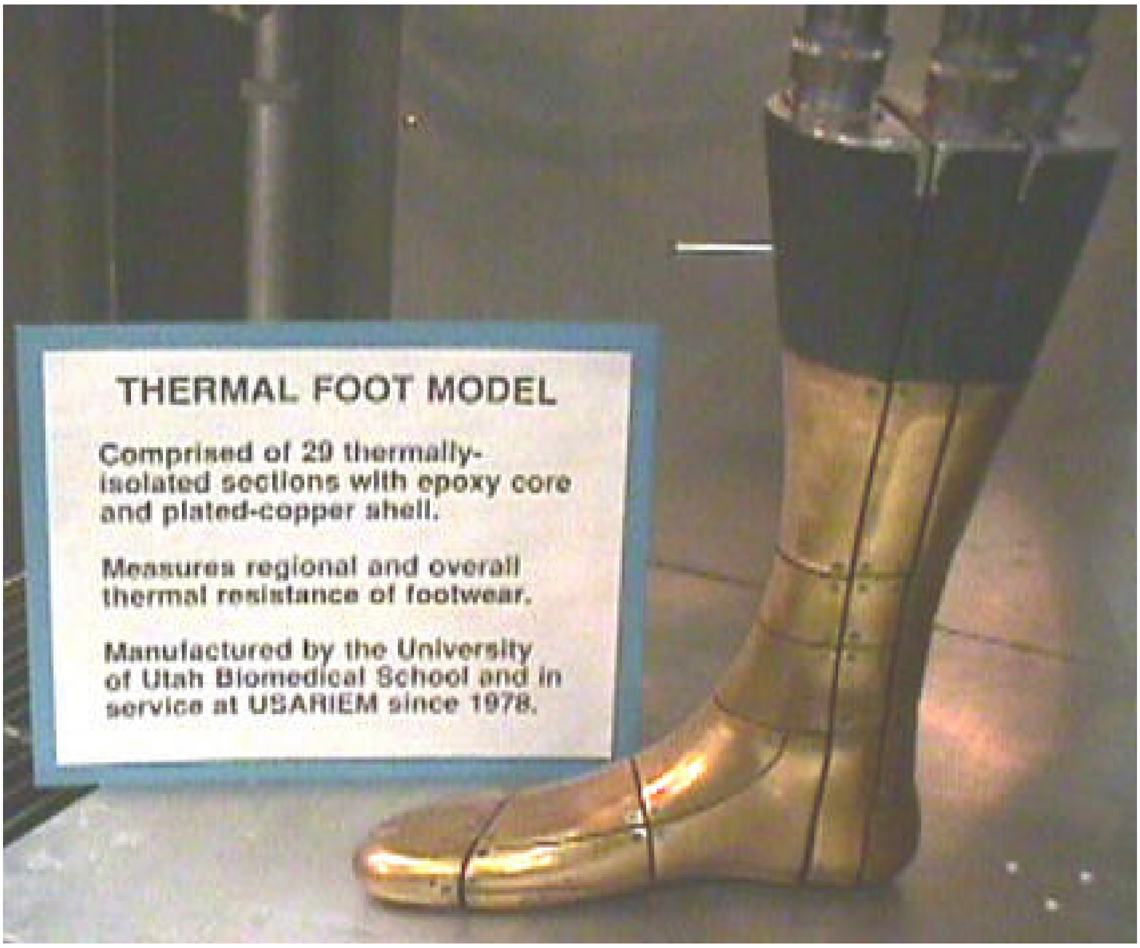

Figure B1. *Foot model at USARIEM.*

Technical description

The current USARIEM Foot Models (Figure B1) are made of copper, 0.125 inches (approximately 3 mm) in thickness, each subdivided into 27 separately heated and controlled measuring sections. Each section has its own heating element cemented to the underside of the copper section in a uniform pattern, and from 1 to 5 small thermistor sensors embedded in the sections at designated locations. The heating elements consist of a length of insulated resistance wire laid back and forth to cover the section to produce the required power density of 300 W/m2. Thermistors (at least 1 per section, 7 in toes, 2 in sole, 5 in heel and 39 in total) are highly responsive, embedded and attached to the section using a copper filled epoxy. The sections are supported by a synthetic foam epoxy structure, which forms the inner core of the foot. Each section is fastened to the epoxy structure with four screws and embedded inserts. All electrical wiring to heaters and thermistors is routed through tubes embedded in the inner epoxy structure.

To help place the foot model into test footwear, the model is separated into three vertical subassemblies. The toe or front subassembly is dressed with the test sock(s) and inserted into the footwear, followed by the insertion of the heel or rear subassembly. Finally, the center subassembly is placed between the other two to complete the insertion of the entire foot model. Slotted inserts are incorporated between the three subassemblies to guide the center into place. The center insert guide has a projection, which locks the lower part of all subassemblies together while a bolt inserted through the front secures the upper subassemblies and center subassemblies screwing into the rear subassembly.

A HP automated data acquisition system continuously scans every section of the foot model for temperature deviation from setpoint and then controls the adjustment of power input to the model. The acquisition system calculates numerous different thermal resistance values (m^2°C/W) from the model: all 29 individual sections; overall foot model; overall less zones 1, 2, 3, and/or 4, and toes. The set temperature for the foot surface is normally controlled at 30-33 °C. Normally footwear is tested at 20 °C, wind 0.1 m/s, 50 % RH. These conditions come from an ASTM standard for testing leather.

Commonly footwear of size US 10 is tested, although, tests on footwear that has ranged from size US 9 to 11 have been carried out.

Annex C. Foot model at VTT

The foot model is divided into 9 zones. Each zone has its own heating and thermometric system. The surface of the foot is heated to a temperature corresponding to the human skin temperature and the power input, which is required to maintain this surface temperature, is measured. Water is supplied to the foot's surface through ”sweat glands”. On the surface water evaporates similar to human sweat. The size of the foot is 42 or 43 depending on the design of the footwear.

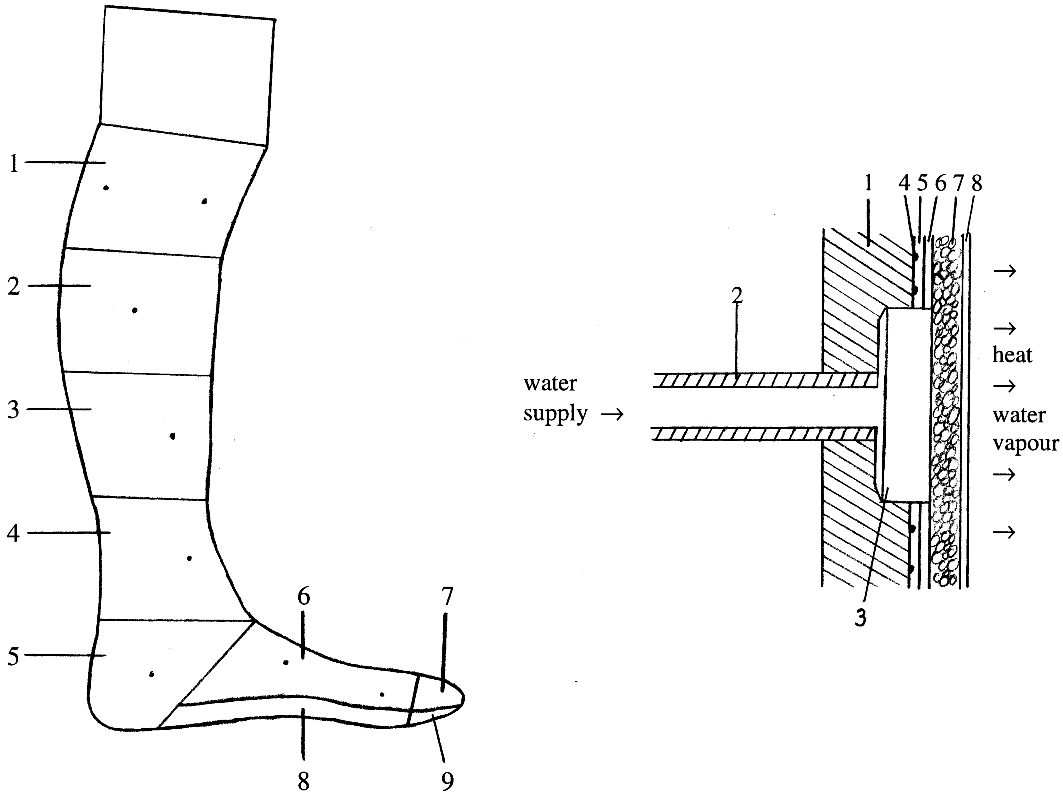

Figure C1. *The zones of the foot model and cross section of one sweat gland.*

Table C1. *Characteristics of the thermal foot model.*

Zone	Surface area (cm^2)	Number of sweat glands
1	340	4
2	330	4
3	270	3
4	240	3
5	160	2
6	170	3
7	50	1
8	160	3
9	40	1

The foot consists of two parts, which can be separated to ease the dressing of footwear. One part consists of the heel and the calf and the other consists of the foot. Above the calf there is a lid through which the water and heating connections are arranged. Figure C1 shows the zones of the foot and the surface structure. The plastic shell (1) is cast in hard foamed plastic and has altogether 24 holes drilled in it for fine water capillaries (2). Water is supplied through small metal tubes and a small sinter glass disc (3) evens out the water supply to the skin. The outer surface of the wall is covered with an electric heating wire (4), which is protected by an insulating film (5). A metal layer (6) evens out the heat over the surface. The surface material is a laminate (7) which spreads the water from the capillaries over a wider area. The outside cover of microporous PTFE (8) allows water to pass through in the vapour but not in the liquid phase. The surface areas of different zones and the amount of sweat glands in each zone are shown in Table C1 and foot dimensions in Figure C2.

The foot is controlled and data is recorded automatically by a computer. The amount of condensed water is determined by weighing the footwear before and after the test.

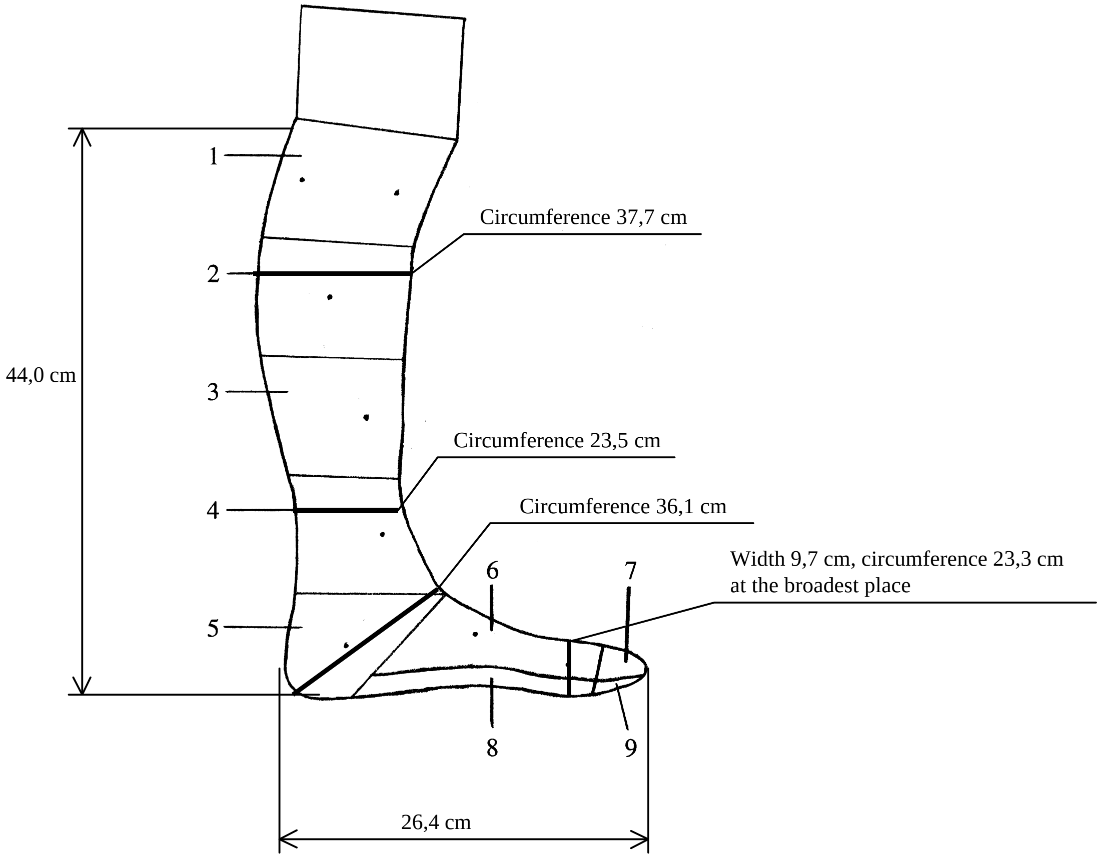

Figure C2. *The dimensions of the foot model.*

The thermal resistance of each section is calculated according to the formula below:

$$R_{tot} = \frac{t_s - t_a}{P} \cdot A \quad (m^2 \cdot °C / W)$$

t_s = surface temperature of a zone (°C)
t_a = ambient air temperature (°C)
P = power input to a zone (W)
A = area of a zone (m^2)

The power input is partly used to evaporate the water. To take this into account, a corrected thermal resistance value is calculated:

$$R_{corr} = \frac{t_s - t_a}{P - P_e} \cdot A \quad (m^2 \cdot °C / W)$$

P_e = evaporative heat loss (W), which is calculated according to the amount of evaporated water.