International Journal of Occupational Safety and Ergonomics
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tose20

Effect of Sweating on Insulation of Footwear

Kalev Kuklane[a] & Ingvar Holmér[a]
[a] National Institute for Working Life, Sweden
Published online: 08 Jan 2015.

INTERNATIONAL JOURNAL OF
OCCUPATIONAL SAFETY AND ERGONOMICS 1998, VOL. 4, NO. 2, 123–136

Effect of Sweating on Insulation of Footwear

Kalev Kuklane*
Ingvar Holmér

National Institute for Working Life, Sweden

The study aimed to find out the influence of sweating on footwear insulation with a thermal foot model. Simultaneously, the influence of applied weight (35 kg), sock, and steel toe cap were studied. Water to 3 sweat glands was supplied with a pump at the rate of 10 g/hr in total. Four models of boots with steel toe caps were tested. The same models were manufactured also without steel toe. Sweating reduced footwear insulation 19–25% (30–37% in toes). During static conditions, only a minimal amount of sweat evaporated from boots. Weight affected sole insulation: Reduction depended on compressibility of sole material. The influence of steel toe varied with insulation. The method of thermal foot model appears to be a practical tool for footwear evaluation.

sweating thermal foot model insulation of footwear cold protection
safety shoes steel toe cap

1. INTRODUCTION

Cold feet and toes are common problems at various jobs and activities. According to the results of the study by Bergquist and Abeysekera (1994), the demand for thermal comfort of cold weather safety shoes was ranked second after fitness and before protection from work hazards. Therefore, it is important to choose shoes with proper insulation properties for various jobs. Thermal comfort of feet does not depend only on the insulation of footwear, but also on the humidity level in the boots, boot material, activity, and so forth. However,

* Presently a doctoral student at the Division of Industrial Ergonomics, Luleå University of Technology, Sweden.

Thanks to Arbesko Gruppen AB and Sweden Boots AB for supplying the boots.

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

the present standard for testing footwear (EN 344; Comité Européen de Normalisation, 1992) does not give a good answer on various aspects of thermal protection provided by footwear. This test method does not provide feedback to the manufacturers on the weak points in the construction, either. Bergquist, Grahn, and Holmér (1994) described various methods for measuring the thermal protection of footwear. The method used by Endrusick, Santee, DiRaimo, Blanchard, and Gonzales (1992) is one of them. In this method, an Automated Foot Model was used in dry conditions and after an 18-hr immersion in 8 cm of water. Bergquist and Holmér (1995) suggest a dynamic method for determining dry heat loss from footwear. In their study the effects of weight and size were studied, too.

This study aimed to look at the effects on thermal insulation of wetting footwear from the inside. Various boots were used in this study to give a relevant basis for further studies with human subjects. In addition, the effect of steel toe cap was studied.

Figure 1. Thermal foot model. *Notes.* Zones: 1—toes; 2—mid-sole; 3—heel; 4—mid-foot; 5—ankle; 6—lower calf; 7—mid-calf; 8—guard.

2. METHODS

The measuring principles are described more precisely by Bergquist and Holmér (1995). The foot model (Figure 1) is divided into 8 zones. Surface temperature and power to each zone is controlled separately with a regulation computer. Heat losses from each zone are recorded. Knowing heat losses, zone areas, and surface and ambient air temperatures it is possible to calculate insulation values for each zone. The model has 3 "sweat glands": one on top of the toe zone, a second one under the sole at the border of heel and sole zones, and a third on the medial side of the ankle zone.

The tests were carried out under standardised conditions: chamber temperature +3 ± 0.5 °C, wind 0.15 ± 0.05 m/s. The foot model was placed in an upright position on a copper-and-zinc alloy plate (Figure 2). The duration of each test was 90 min and each condition was tested

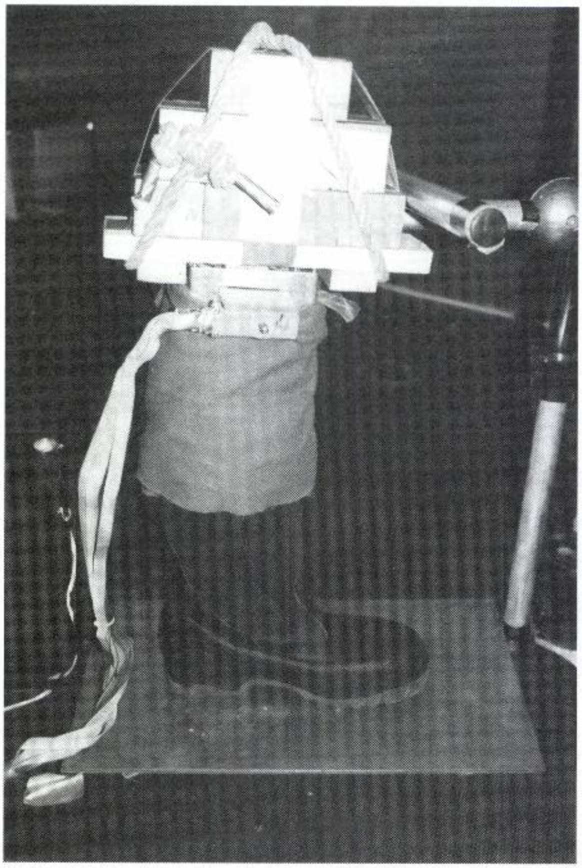

Figure 2. Setup for insulation measurements with thermal foot model.

twice. The limit difference of the two runs had to be less than 0.01 m² °C/W. If the difference was greater, an additional test was carried out until two values satisfied the demand. However, in most cases two runs were sufficient. The averages of the two values were used in analysis. Between the tests the boots were left at room temperature (21 ± 0.5 °C, relative humidity 33 ± 5%).

Total insulation was defined as the insulation from toes to ankle (zones 1–5, Figure 1) according to formula

$$I_{t,r} = (\overline{T_s} - T_a)/(\Sigma P_i/\Sigma A_i),$$

where P_i—power to each zone, A_i—area of each zone, $\overline{T_s}$—mean surface temperature, T_a—ambient air temperature.

3. MATERIAL AND PROCEDURE

All the tests were carried out when the foot was standing. Four types of boots were used: models 520, 533, and 536 from Arbesko Gruppen AB, and a rubber boot from Sweden Boots AB (Figure 3). All the models have steel toe cap. The manufacturers produced the same models without steel toe cap especially for research purposes. The coding of the boots and boot data are shown in Table 1. Boots of size 41 were used for the test. The boots were chosen so that a wide range of insulation values could be represented, from rubber boots to heavy winter boots.

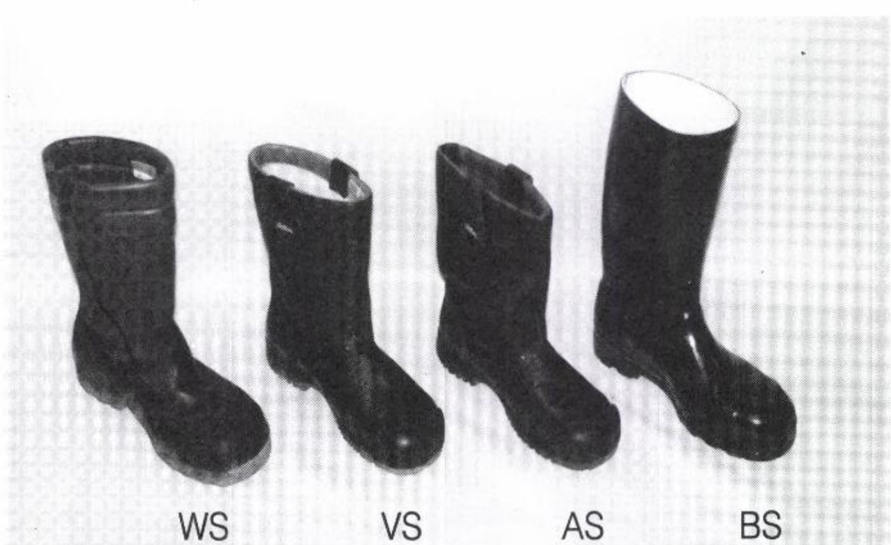

Figure 3. The four types of boots that were used in the study.

TABLE 1. Boot Data

Model	Manufacturer	Code	Material	Colour	Weight (g)	Height (cm)
533*	Stålex, Sweden	An	Leather	Black	634	28
533	Stålex, Sweden	As	Leather	Black	753	28
*	Sweden Boots	Bn	Rubber	Black	888	36
	Sweden Boots	Bs	Rubber	Black	1011	36
536*	Stålex, Sweden	Vn	Leather, Nylon fur	Black	706	28
536	Stålex, Sweden	Vs	Leather, Nylon fur	Black	806	28
520*	Stålex, Sweden	Wn	Leather, Thinsulate	Black/Green	724	32
520	Stålex, Sweden	Ws	Leather, Thinsulate	Black/Green	791	32

Notes. * Boot without steel toe cap (made only for research purposes).

Six conditions were used for testing the boots (Table 2). These six conditions combine three parameters: dry-wet, the use of weight, and a change of insulation with a sock. In wet conditions, water was supplied with a peristaltic pump (Pretech Instruments, Gilson). The flow was regulated to be 10 g/hr, that is, from each gland came around 3.3 g/hr. For the 90-min test, the total water supply was 15 g. A thin sock was used for better water distribution (data on socks is shown in Table 3). The weight of the boot and sock was measured at the beginning and end of each trial. The water tubes to the foot were insulated and the water temperature was kept at 34 °C. The tests were repeated when the boots had dried again to the weight level of dry tests.

TABLE 2. Combination of Measurements Conditions

Abbreviation	Dry-Wet	Use of Weight (35 kg)	Sock
DNN	Dry	No	N
DW1	Dry	Yes	1
DN2	Dry	No	2
DW2	Dry	Yes	2
WN2	Wet	No	2
WW2	Wet	Yes	2

Notes. The first symbol in an abbreviation determines dry (D) or wet (W), the second determines the use of weight—yes (W) or no (N)—and the third shows the use of sock: no sock (N), thick sock (1), or thin sock (2).

The insulation values of air layer (bare foot) and both socks were measured in a dry condition with no weight at room temperature. The results of these measurements are shown in Table 3.

TABLE 3. Data on Air Layer (N, Measured with Bare Foot) and Sock Insulation (m^2 °C/W) in Some Zones and Zone Groups

Sock	Code	Material	Colour	Weight (g)	Toes	Heel	Sole	Heel	Sole and Foot Zones	Foot Zones and Ankle
Sock 1	1	Polyester	Blue	34	0.162	0.143	0.172	0.156	0.155	0.155
Sock 2	2	70% Cotton 30% Polyamide	White	20	0.127	0.110	0.136	0.121	0.127	0.133
No Sock	N				0.111	0.089	0.120	0.101	0.104	0.101

Notes. The values were measured in dry conditions. The foot was placed in an upright position on a copper/zinc alloy plate without weight.

4. RESULTS

The mean difference and standard deviation for the double determinations for the insulation of the whole shoe was 0.004 ± 0.003 m^2 °C/W and for the toe zone 0.004 ± 0.004 m^2 °C/W in dry conditions and, respectively, 0.006 ± 0.006 m^2 °C/W and 0.004 ± 0.003 m^2 °C/W in wet conditions. The difference between replicates in dry conditions was less than 2% of the mean value for all measurements, and less than 3% for wet conditions. Differences between means of double determinations for different shoes exceeding 4% in dry and 6% in wet conditions would then be significant ($p < .05$). The values for dry conditions agree with previous results from the study by Bergquist and Holmér (1995) on another foot model.

The results can be seen in Figures 4–9. Table 4 shows the weight gain in boots due to sweating. Only a small amount of water was evaporating through the boots. The boots with an insulation layer had less water in socks than the boots without it. Table 5 gives the amount of water left in boots 1 day after the wet test. The insulation of boots Vs and Vn is not easily comparable because at a closer examination of the boots it came out that Vn did not have an insulation layer of nylon fibres in toe zone. Figure 9 shows the differences in insulation values from dry and wet tests without weight.

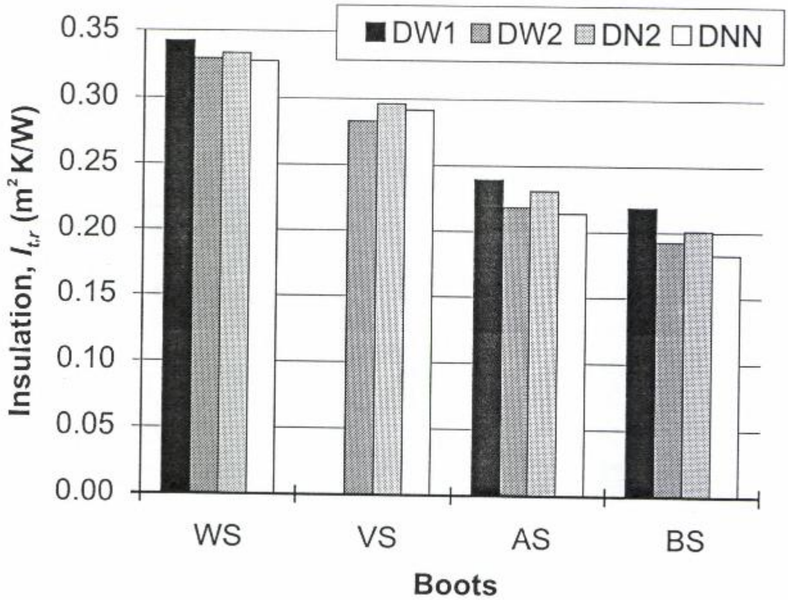

Figure 4. Effect of sock. Zones from toes up to and including ankle. *Notes.* All are dry tests. DW1—sock 1 with weight; DW2—sock 2 with weight; DN2—sock 2 without weight; DNN—no sock, no weight.

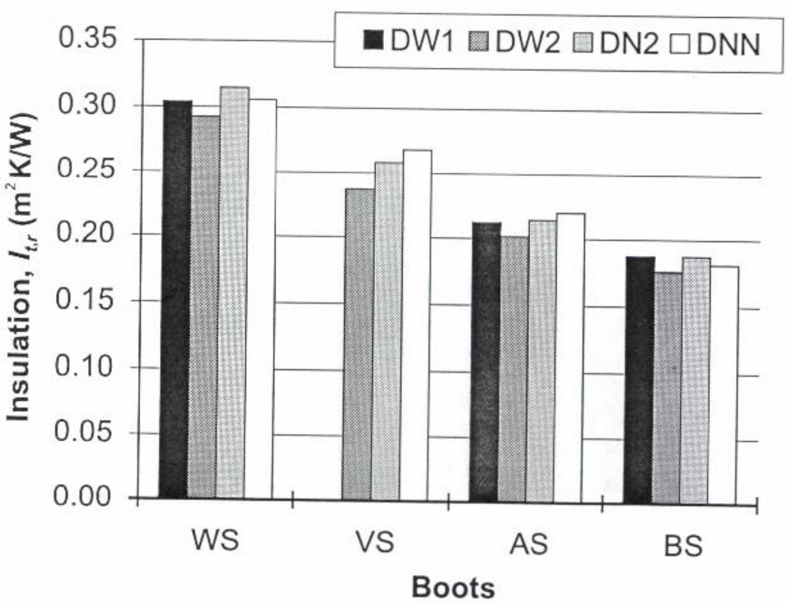

Figure 5. Effect of sock. Heel zone. *Notes.* All are dry tests. DW1—sock 1 with weight; DW2—sock 2 with weight; DN2—sock 2 without weight; DNN—no sock, no weight.

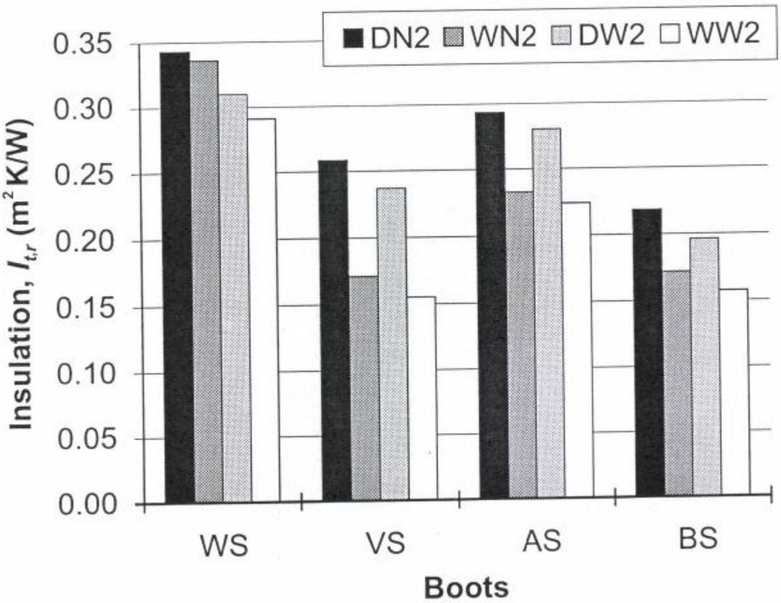

Figure 6. Effect of wetting and weight. Sole zone. *Notes.* All tests are with sock 2. DN2—dry without weight; WN2—wet without weight; DW2—dry with weight; WW2—wet with weight.

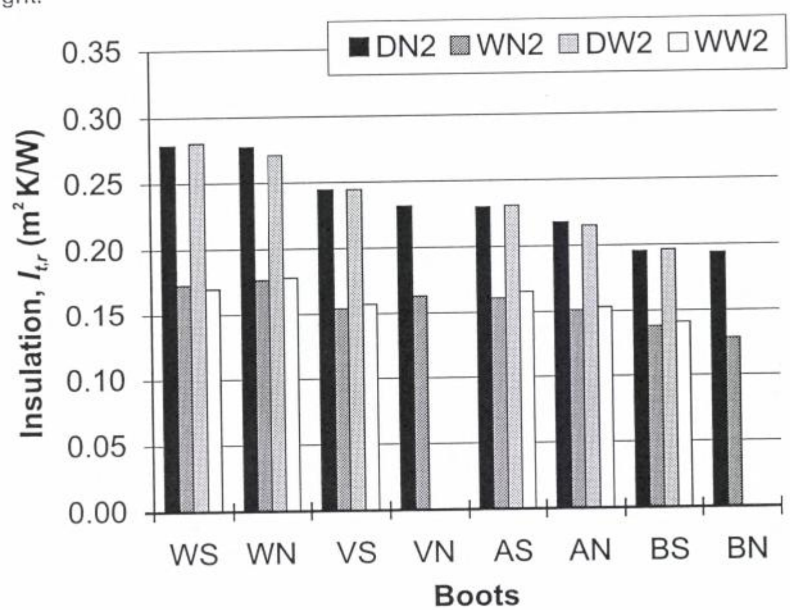

Figure 7. Effect of wetting and weight. Toe zone. Notes. All tests are with sock 2. DN2—dry without weight; WN2—wet without weight; DW2—dry with weight; WW2—wet with weight.

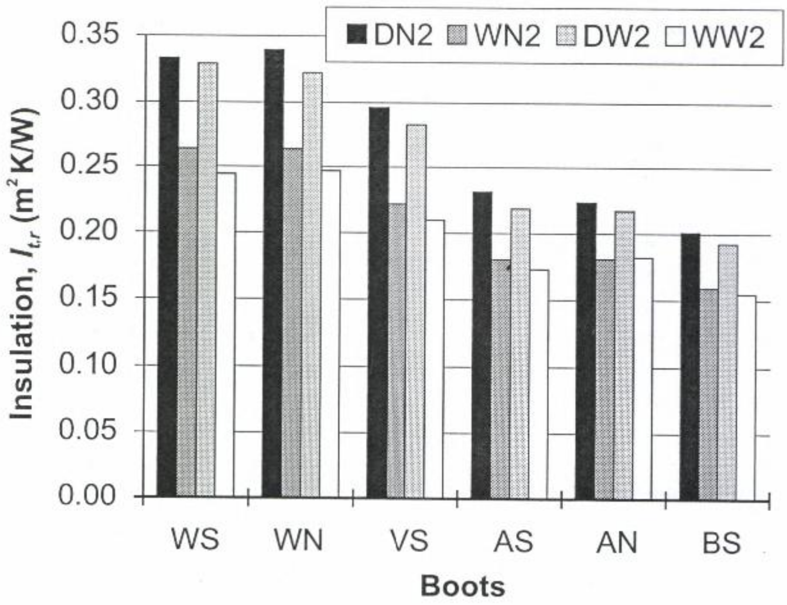

Figure 8. Effect of wetting and weight. Zones from toes up to and including ankle. *Notes.* All tests are with sock 2. DN2—dry without weight; WN2—wet without weight; DW2—dry with weight; WW2—wet with weight.

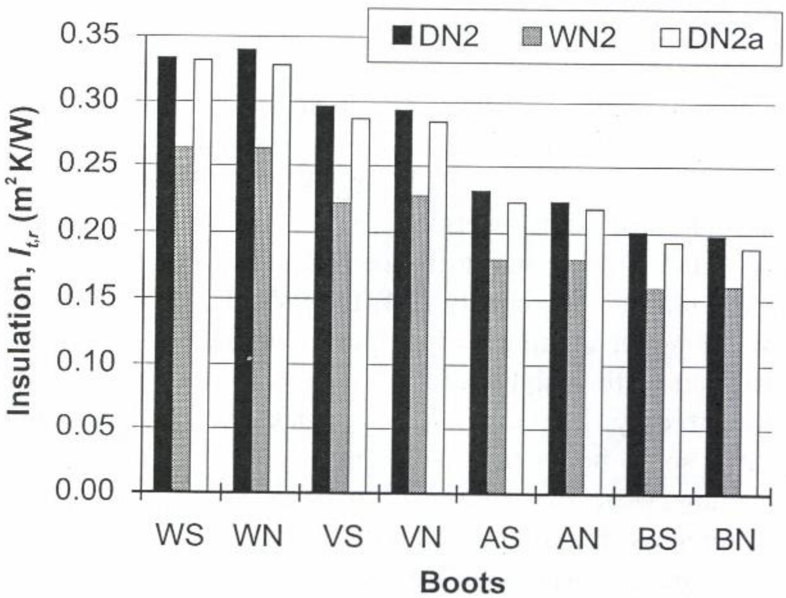

Figure 9. Effect of wetting and drying. Zones from toes up to and including ankle. *Notes.* All tests are with sock 2. DN2—dry without weight; WN2—wet without weight; DN2a—dry test 1 day after wet test (single test and not double determination like others).

TABLE 4. Water Gain in Boots and Socks During Sweating Tests: Without Weight (WN2) and With Weight (WW2)

	WN2				WW2			
Boot type	Boot and Sock (g)	Boot (g)	Sock (g)	Evaporation (g)	Boot and Sock (g)	Boot (g)	Sock (g)	Evaporation (g)
An	14.0	9.4	4.6	1.0	13.2	8.8	4.4	1.8
As	13.7	8.6	5.1	1.3	12.9	8.3	4.6	2.1
Bn	13.9	7.9	6.0	1.1				
Bs	14.0	8.1	5.9	1.0	14.1	9.4	4.7	0.9
Vn	14.1	9.2	4.9	0.9				
Vs	14.2	9.7	4.5	0.8	14.3	9.6	4.7	0.7
Wn	14.6	10.7	3.9	0.4	15.0	10.8	4.2	0.0
Ws	14.5	10.2	4.3	0.5	14.6	10.8	3.8	0.4

Notes. Total water supply to the boots was 15 g (10 g/hr).

TABLE 5. Water Left in Boot 1 Day After Test WN2

Boot	An	As	Bn	Bs	Vn	Vs	Wn	Ws
Weight Difference (g)	2.3	1.1	0.0	0.0	2.4	6.7	4.7	5.7

A dry test was carried out 1 day after the wet test to check the reduction of insulation. There was still a slight influence from the water that was left in the boots (Figure 9). Figures 6–8 show the effects of weight and sweating (DN2, DW2, WN2, and WW2) on the sole and toe zone, and total insulation levels.

Figures 4 and 5 show the influence of the sock on the boot and the heel zone insulation, respectively (DW1, DW2, DN2, and DNN). DN2 was added for better comparison as the test with the thick sock (DW1) was carried out with weight and the test with the bare foot (DNN) without weight only. The test with the thick sock (1) was carried out specially with some boots that were later used in a study with human subjects as they wore the same type of sock.

The differences in total insulation between the boots with and without steel toe cap were not significant. The toe zones of boots As and Bs had significantly higher insulation than boots An and Bn in dry and wet conditions. Vs had significantly higher insulation than Vn in dry conditions, but not in wet conditions. Ws and Wn did not differ in their insulation levels. However, if in dry conditions toe zones of Ws and Vs had somewhat higher insulation than Wn and Vn, then in wet condition the situation was the opposite. Even in An the reduction of insulation compared to As was somewhat smaller in the wet condition than in the dry (Figure 7).

5. DISCUSSION

Sweating strongly reduced the insulation values of the boots (Figures 6–8). There are two reasons for this:

1. the evaporative heat loss in addition to dry heat loss,
2. the drop in effective insulation due to wetted layers.

The second reason explains why the drop in insulation was higher in thick boots (W and V). The toe insulation in these boots dropped clearly to the same level with boots A and B, whereas B still had the lowest insulation (Figure 7).

Sweating had minimal effect on the sole insulation of boot W. Boot W has thick felt soles. This type of sole was greatly affected by added weight (Figure 6). Still, the combined effect of weight and sweating for the sole of this boot was less than the same effect in the other boots. Weight in the other boots had a small effect on sole and heel insulation, and no effect for the other zones. This agrees with the results by Bergquist and Holmér (1995) that weight has an influence on the sole insulation and total insulation is minimally affected. This study shows that weight influence depends also on sole material.

The study by Endrusick et al. (1992) showed a considerable reduction of thermal resistance of the footwear that were immersed for 18 hrs in 8 cm of water. These reductions were in the same range as the reductions observed in this study. However, due to inside water supply (sweating) a similar reduction occurred already after 1.5 hrs. The insulation decrease in an insulated rubber boot was minimal during immersion test (Endrusick et al., 1992). Basing on the results of this study, it could be predicted that in conditions of high activity and sweating the reduction in insulation of those boots could be important. The possible effect of sweating as well as the consequences of punctuation were discussed also by Endrusick et al. (1992).

There are slight differences in evaporation and water gain in socks. Boots with insulation (W and V) had a lower amount of water in socks because the insulation could absorb water better. A similar effect occurred with added weight where better contact between first water distributor (sock) and boot material allowed water to move further to boot material. The evaporation of water was, however, more difficult. During walking the effect of evaporation could be bigger than measured in static conditions. Anyway, more water will be collecting in boots with insulation and it also means that these boots take more time for drying.

It was important to know after how many days it would be possible to continue with testing. When the insulation was measured in dry conditions 1 day after wet measurements, the insulation values were somewhat lower but not significantly different of the dry tests not preceded by the wet tests (Table 4 and Figure 9). All water had not evaporated from the boots by this time. The amount of water that stayed in boots with higher insulation after 1 day was slightly greater for boots with steel toe cap (Table 5). Probably, a similar tendency is present also in real wear conditions where boots are used at about 15-hr intervals.

The effect of water in boots was great and its influence can be significant. The evaporation from boots during tests seemed to be somewhat higher in boots with steel toe cap (Table 4). In dry conditions, the insulation of boots with steel toe cap was generally higher than in boots without, but in wet conditions the general tendency was opposite (Figures 7 and 8). The effects of humidity in boots with steel toe cap seem to be worth further study.

The warmest boots were W, followed by V and A. The rubber boots (B) had the lowest insulation. For all boots, the sole had highest insulation in all conditions. The condition with a thick sock was the warmest for all boots (Figure 4). For the boots without a special insulation layer (A and B) the coldest zone seemed to be the heel (Figure 5). Generally, the insulation of these boots in all zones was at the same level. For the boots with a special insulation layer (W and V), the coldest zone was toes and it was considerably lower than the total value for all foot zones and ankle. The toe insulation of boots W and V, in comparison with other zones, was closest to these of boots with no special insulation, especially in wet conditions.

6. CONCLUSIONS

1. Felt seems to be a material that maintains insulation well both without and with sweating.

2. The boots with lower insulation (A and B) had more homogenous insulation distribution than the boots with higher insulation.
3. The toe insulation of cold weather footwear (W and V) was relatively low and could be improved.
4. Wetting reduced insulation by 19 to 25%. In toes, the insulation reduction was up to 30% for boots with lower insulation and up to 37% in boots with higher insulation.
5. Wetting generally reduced insulation 1–3% more in boots with steel toe cap, than in boots without. In the toe zone, the difference in reduction was greater for boots with higher insulation (3–7%).
6. The effect of steel toe cap varied with insulation: Boots with lower insulation gained insulation (additional layer) even in wet conditions, whereas in boots with higher insulation this effect was negligible. In wet conditions, the effect of steel toe was negative for boots with higher insulation.
7. Only a minimal amount of sweat, approximately 6%, evaporated from boots while standing.
8. Weight reduced insulation of boots. In dry conditions, the reduction of insulation due to weight was 3–4%, whereas in wet conditions the insulation of boots with high insulation was diminished by 6–7% and in boots with low insulation up to 3%.
9. The sole insulation was affected more by weight. In dry conditions, the reduction was 4–5% for boots with lower insulation and 7–8% for boots with higher insulation. In wet conditions, the sole material and construction have bigger influence and the variability was higher. The insulation reduction was in some boots up to 13–14%.
10. Thick socks compared to thin socks added around 5 to 11% depending on boot insulation.
11. The thermal foot method appears to be a practical tool for thermal evaluation of footwear.

REFERENCES

Bergquist, K., & Abeysekera, J. (1994). Ergonomics aspects of safety shoes worn in the cold climate. In *Proceedings of the 3rd Pan-Pacific Conference on Occupational Ergonomics, Seoul, Korea* (pp. 590–594). Seoul, Korea: Ergonomic Society of Korea.

Bergquist, K., Grahn, S., & Holmér, I. (1994). A method for measuring the thermal protection provided by footwear. In *Proceedings of the Second International Congress* on Physiological Anthropology (pp. 330–333). Kiel, Germany: German Society of Physiological Anthropology and Japanese Society of Physiological Anthropology.

Bergquist, K., & Holmér, I. (1995). A method for dynamic measurement of the resistance to dry heat exchange by footwear. In K.M. Bergquist (Ed.), *Ergonomiska krav på skyddsskor i kallt klimat* [Ergonomic demands on safety shoes in cold climate] (pp.93–120). Licentiate thesis. Luleå, Sweden: Luleå University.

Comité Européen de Normalisation. (1992). *Requirements and test methods for safety, protective and occupational footwear for professional use* (Standard No. EN 344: 1992). Brussels, Belgium: Author.

Endrusick, T.L., Santee, W.R., DiRaimo, D.A., Blanchard, L.A., & Gonzales, R.R. (1992). Physiological responses while wearing protective footwear in a cold-wet environment. In J. McBriarty & N. Henry (Eds.), *Performance of Protective Clothing: Fourth volume* (STP 1133, pp. 544–556). Philadelphia: American Society of Testing and Materials.