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Footwear for cold environments

Thermal properties, performance and testing

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For my family:
the ones who were,
the ones who are,
the ones to come.

List of original papers

The thesis is based on following papers and some unpublished data. Papers are presented under Appendices:

I Kuklane K, Geng Q & Holmér I (1999) Thermal effects of steel toe caps in footgear. *International Journal of Industrial Ergonomics,* 23(5-6), 431-438.

II Kuklane K, Geng Q & Holmér I (1998) Effect of footwear insulation on thermal responses in the cold. *International Journal of Occupational Safety and Ergonomics,* 4(2), 137-152.

III Kuklane K & Holmér I (1998) Effect of sweating on insulation of footwear. *International Journal of Occupational Safety and Ergonomics,* 4(2), 123-136.

IV Kuklane K, Holmér I & Giesbrecht G (1999) Change of footwear insulation at various sweating rates. *Applied Human Science,* 18(5), 161-168.

V Kuklane K & Holmér I (1997) Reduction of footwear insulation due to walking and sweating: a preliminary study. In: Holmér I & Kuklane K eds. *Problems with cold work.* Arbete och Hälsa 1998:18. Pp 96-98, Stockholm: National Institute for Working Life.

VI Kuklane K, Holmér I & Giesbrecht G (1999) One week sweating simulation test with a thermal foot model*. The Third International Meeting on Thermal Manikin Testing,* National Institute for Working Life, Stockholm, Sweden.

VII Kuklane K, Gavhed D & Fredriksson K (1999) A field study in dairy farms: thermal condition of feet. *10th Year Anniversary Ergonomic Conference,* Luleå University of Technology, Sweden, 110-116.

VIII Kuklane K, Afanasieva R, Burmistrova O, Bessonova N & Holmér I (1999) Determination of heat loss from the feet and insulation of the footwear. *International Journal of Occupational Safety and Ergonomics,* 5(4), 465-476.

IX Kuklane K, Holmér I & Afanasieva R (1999) A comparison of two methods of determining thermal properties of footwear. *International Journal of Occupational Safety and Ergonomics*, 5(4), 477-484.

X Kuklane K, Holmér I & Havenith G (2000) Validation of a model for prediction of skin temperatures in footwear. *Applied Human Science,* 19(1).

Contents

1. Literature review and introduction

1.1 Basic information

Air temperature, radiant temperature, humidity and air velocity are the four environmental factors which affect human responses to thermal environments. Their combination with the parameters of metabolic heat generated by human activity and clothing worn by a person provides the six basic factors which define human thermal environments (Parsons, 1993). The stress of thermal environment results from a complex interaction of these six factors (Holmér, 1991).

The severity of the environment is determined by the conditions for the maintenance of heat balance (Holmér, 1991). Cold is a sensation that results from heat loss. Cold is regarded by workers in such conditions as the main cause of accidents, illness and different types of complaints (Enander et al., 1979).

1.2 Effects of cold

A good review on the latest research on cold was given at the International Symposium on Problems with Cold Work (Holmér et al., 1998). It discussed various cold stress and risk assessment strategies (Afanasieva, 1997; Conway et al., 1997; Holmér, 1997; Keatinge, 1997; Rintamäki et al., 1997; Tikuisis, 1997), cold adaptation (Bittel, 1997; Janský, 1997), physiological and practical problems in cold (Giesbrecht, 1997; Griefahn, 1997; Risikko et al., 1997; Schagatay et al., 1997) etc.

The primary control centre for thermoregulation is in the hypothalamus (Parsons, 1993). The input to the hypothalamus from temperature sensitive nerve endings is decisive for the intensity of the heat production (Reinertsen, 1990). In a cold environment, this control system will try to maintain thermal balance. Conservation of heat is achieved by thermoregulation. It is brought about by a reduction of blood flow to the surface and a counter current heat exchange between arterial and venous blood. For example, under cold conditions the arterial blood enters the foot at a temperature of about 30 °C (Love, 1948). When cold receptors are excited, more heat is produced by increasing the metabolic rate and heat loss is diminished by decrease in peripheral circulation in order to preserve thermal homeostasis of the central part of the body (Schmidt, 1978). This protective response causes a drop in skin temperature and may also cause shivering. Vasoconstriction causes cooling of the extremities, which will diminish muscle power and performance since a considerable proportion of the muscles are situated in the legs and arms (Rintamäki et al., 1992). It also reduces skin blood flow causing a loss in sensitivity (Parsons, 1993).

Experimental evidence indicates that even relatively mild thermal stress may affect human performance. The deterioration in manual performance is associated with lower hand-skin temperature (Enander, 1989; Sanders et al., 1987). Grip strength decreases when hands are cooled. The electrical activity of the most superficial muscle fibres drops due to cooling (Vincent et al., 1988). If temperature falls muscles become stiff and blood viscosity increases and movements become clumsy (Parsons, 1993). Movements involving the fingers are affected more than those of the hands (Sanders & McCormick, 1987). Cold affects sensitivity, strength, simple and complex movements. The negative effects of cold are the changes in mechanical properties of the skin, effects on biomechanical processes at nerve or receptor level, loss of muscle strength and increased viscosity of the synovial fluid in the joints (Enander, 1986). In addition, discomfort and shivering provide distractions and cause behavioural changes (Parsons, 1993). The risk of accidents and injuries is greater in situations involving rapid work under stress or use of sharp implements (Enander, 1986).

For freezing injuries, pinching pain is the first symptom. This sensation disappears before the actual freezing takes place as nerve conductivity is abolished below +7 °C in the tissue. Later sensation fails totally. For non-freezing injuries numbness, paraesthesia and pain disturbing sleep can be the first signs (Granberg, 1990). When hypothermia develops, the victim is often apathetic, feeling weak and not volitional to start his muscle activity (Granberg, 1990).

1.3 Protection from cold

There are two approaches to prevent cold injuries (Påsche et al., 1990):

- to increase heat production;
- to reduce heat losses.

In the cold, a higher insulation value means less heat loss and more efficient protection against body cooling (Holmér, 1987). A man who is comfortably dressed for inactivity will be grossly overdressed for hard work in the same ambient temperature, and vice versa (Haisman, 1988). Moisture, e.g. sweat, that collects in clothing causes problems, especially when periods with high activity are followed by periods of low activity (Gavhed, 1996; Påsche et al., 1990). Clothing must often provide protection against hazardous substances, but at the same time allow vapour permeability (Nielsen, 1991). The right choice of clothing for work in cold is thus important (Afanasieva, 1977; Holmér, 1988).

Several studies have demonstrated rapid cooling of the feet while standing still (Enander et al., 1979; Williamson et al., 1984). This can be attributed to a decreased heat production and reduced blood flow to the extremities (Nielsen et al., 1985). The inactive man exposed to cold climate and dressed in conventional cold-weather clothing experiences difficulty in maintaining the temperature of the hands and feet. Comfort and performance are degraded as the temperature of the extremities falls with duration of exposure (Haisman, 1988). To protect the feet from cold we need to have properly insulated footwear. Here the term “safety footwear” covers all type of cold climate footwear. Many activities in the cold still need the protection of toes with steel cap, too.

Electrical heating is a form of auxiliary heating which can offer a solution in some circumstances and is most useful when the wearer can conveniently connect to a power supply of a vehicle or some other type of equipment (Haisman, 1988). Other methods of keeping extremities and whole body warm are important. For example, breaks and warm-ups can be arranged and clothing design should allow easy doffing and donning to provide possibility for condensed humidity to evaporate (Nielsen, 1991).

Another way to avoid cooling is exercise. The human body is constantly producing heat. At rest it is about 50 W, but can easily rise to 500 W or more for short periods of very heavy activity (Crockford, 1979). Exercise intensity is critical for possible exposure time. The more heat that is available for the extremities, the longer is the exposure time (Holmér, 1991).

Working muscle groups are the sites of local heat production and moreover, working with a large mass of leg muscles stimulates circulation in the feet which is known to be directly related to foot temperature (Rintamäki et al., 1989b). For cold climate outdoor activities we cannot forget snow. Metabolic energy expenditure for walking in snow grows as the footprint depth increases (Pandolf et al., 1976).

1.4 Feet and boots

A thorough literature survey on various aspects of feet and cold weather footwear has been written by Bergquist (Bergquist, 1995) as a part of her licentiate thesis and by Hagberg and co-workers (Hagberg et al., 1983).

1.4.1 Feet in cold

The extremities are more affected by the cold exposure compared to other parts of the body. The hands and feet have a surface area which is very large in relation to their volume (Williamson et al., 1984). Due to the unfavourable surface to mass ratio of human extremities these parts suffer exceptionally high rates of heat loss (Holmér, 1991).

Extremities have little local metabolic heat production because of their small muscle mass and this falls with tissue temperature. For example, each foot may generate up to 2 W, but at tissue temperatures below about 10 °C this may be reduced to about 0.2 W (Dyck, 1992; Oakley, 1984).

The heat balance of extremities rely greatly upon heat input by warm blood from the body core. Extremity blood flow is under thermoregulatory control and is often reduced in the cold when heat production is moderate or low (Holmér, 1991). The amount of heat given by the blood flow to foot reaches over 30 W in warm conditions or during exercise, but it is greatly reduced by cold and may fall below 3 W (Dyck, 1992; Oakley, 1984).

The third source of heat in feet is heat content of the feet themselves. Each foot at a mean temperature of 35 °C has about 160 kJ of heat above an ambient of 0 °C. Even when the mean tissue temperature falls to 5 °C this is still 23 kJ (Dyck, 1992; Oakley, 1984).

The hands and feet are in frequent contact with cold surfaces compared to other body parts. This further explains, why the extremities are more affected by cold exposure (Bergquist et al., 1994). They are the first parts to be affected by chilling and it is where the results of chilling are most acute (Williamson et al., 1984).

According to statistics regarding cold injuries at work in Sweden, 73% of the cold injuries in 1991 were on the hands and feet (Arbetarskyddsstyrelsen, 1992). No matter how warm the rest of the man's body is, if he has cold and wet feet he will still feel uncomfortable and may get a cold injury (Oakley, 1984).

Humans attain warmth when activity is at its peak. Concurrent sweating contributes to more rapid cooling during low activity (Enander et al., 1979). A study by Love (Love, 1948) showed, that 27 % of the heat lost in the cold from the feet was evaporative loss, and the water loss from the feet often equalled in intensity that from the body. The dependence of sweating on foot skin temperature is obvious (Rintamäki & Hassi, 1989b).

Oakley (Oakley, 1984) studied the performance of military boots under field conditions. The results showed that the toe skin temperatures fell rapidly, especially when the person was inactive in the cold. The toes might warm up during exercise, but fell rapidly when the exercise ceased. This temperate fall could be quicker, if sweating had made the footwear wet. Moisture, either absorbed from the outside or inside reduces the insulation of the footwear. Similar results are reported by Bunten (Bunten, 1982). Endrusick et al (Endrusick et al., 1992) reported a reduction of insulation by up to 35 % after prolonged soak.

Work in the cold with long periods of standing requires high insulation of clothing as well as of boots. The preservation of warm feet in the cold is the result of a balance between heat input by circulatory blood and heat loss. Thus, physiological factors as well as the insulation values of footwear and socks become decisive. Walking results in increased heat production and better blood circulation to feet. Consequently, the foot temperatures will remain higher (Påsche et al., 1990).

If a person generally feels cool, he will often notice it in the feet, since the skin temperature there is normally lowest because of the vasoconstriction. Cold feet may actually be a symptom of general cold discomfort (Fanger, 1972). A study on the effects of added clothing on warmth and comfort in cool conditions showed that the feelings of discomfort of the subjects were associated with cold feet (McIntyre et al., 1975). For improving ordinary indoor thermal conditions, floor heating was recommended, but for outdoor and for some other indoor conditions it cannot be used.

Tanaka et al (Tanaka et al., 1985) showed that cold and pain sensation during immersion of feet into cold water was strongest during the second minute of exposure when the constant skin temperature change was quickest. Later the temperature drop slowed down, and pain and cold sensations reduced. In a study by Tochihara et al (Tochihara et al., 1995) a similar trend was noted. During shorter exposures the rate of skin temperature drop was the same as during longer exposures. However, the constant rate of change was shorter in shorter exposures. Generally, it took longer time with many short exposures to reach the same skin temperature than with few long exposures. There was lower pain and cold sensation during short exposures although final skin temperatures were approximately as low. The cold or pain sensation is often connected with a particular foot part: heel or more often toes. Since thermal sensation depends mostly on the temperature of the coldest part of the leg, then the cold protection of toes is important for comfort (Rintamäki et al., 1989a).

Foot temperature is related to a number of different factors, e.g. activity, insulation and cleanliness (Påsche et al., 1990). The feet are comfortable when the skin temperature is about 33 °C and the relative humidity next to the skin is about 60 % (Oakley, 1984). They start feeling cold at toe temperatures below 25 °C, while discomfort from cold is noted at temperatures under 20-21 °C (Enander et al., 1979). Further decrease of the foot temperature to 20 °C is associated with a strong perception of cold (Luczak, 1991).

It has been found that the hands and feet were particularly vulnerable to cold. In a study by Williamson et al (Williamson et al., 1984), the average toe skin temperature before and after work in a cold store was 28.2 °C and 24.1 °C respectively. For the hands, the difference in skin temperature drop was 7.0 °C (from 30.9 °C), but the increase in discomfort sensation was 14 % for feet, while it was only 10 % for the hands.

1.4.2 Feet injuries and protection

Work performance of people depends to a large extent on their thermal state. For many occupations, e.g. foresters, farmers, industrial and construction workers, military personnel etc., personal mobility is of great importance. Personal mobility depends on legs and feet, and their condition is largely dependent on the footwear. The working conditions dictate the specific footwear type.

In mobile jobs in cold environments one has to deal with intensive sweating in feet due to work, as well as rapid cooling in times of inactivity resulting in discomfort feeling due to high humidity concentration in footwear. Standing jobs, e.g. meat cutting, involve cooling of the feet through intensive heat loss by conduction and lower heat input from blood flow, especially if there is not much possibilities for feet motion and warming them up with exercise. With exercise it is possible to warm up the extremities or at least reduce the cooling, but none of those exercises used in the study by Rintamäki et al (Rintamäki et al., 1992) was able to warm up the toes. The exercise length should probably be longer than 10 minutes to affect the toe skin temperatures. An 8-hour long study (Rissanen et al., 1998) at -10 °C showed that the foot and toe temperatures increased during exercise (240 W/m^2). The quick rewarming of feet during exercise was partly related to pumping warm air from and warm blood through calf muscles. The rewarming of toes started only after 15-20 minutes of the exercise. The later onset of the recovery of the toe skin temperature has been observed also by other authors (Ozaki et al., 1998). Therefore, special attention should be devoted to cold protection and warm-up of the toes.

Combat conditions involve both mobile and standing still situations. An additional trouble in combat conditions is that soldiers often don't have opportunities to take off the boots, dry them or just go somewhere and warm themselves up (Dyck, 1992; McCaig et al., 1986; Oakley, 1984). The most common problems during the Falkland conflict were the bad performance of boots and feet condition (McCaig & Gooderson, 1986).

A lot of data have been recorded about frostbite on feet, trenchfoot etc. The recorded data dates back to the 18th century, when the military medical service started to take real care of soldiers (O'Sullivan et al., 1995). Frostbite occurs when skin temperature falls below its freezing point, i.e. 0.6 °C, and tissue freezes. The recovery period is accompanied by easily visible changes, such as blistering and gangrene (Dyck, 1992; Hamlet, 1997; Oakley, 1984).

Incidence of trenchfoot has been noted in environments with ambient temperatures from just below to well above freezing. Causal factors are cold, wet, immobility, dependency of the feet and tightness of the boots and other restrictions to normal circulation. Typically, the first sign is loss of sensation in the toes (Dyck, 1992; Hamlet, 1997; Oakley, 1984; O'Sullivan et al., 1995). Endrusick and co-workers (Endrusick et al., 1992) have studied non-freezing and other foot injuries, and have shown similar problems.

Providing the feet with adequate insulation is the most important single measure to counteract the injurious effects of cold (Haisman, 1988). Nielsen (Nielsen, 1991) mentioned the possibility of using electrically-heated socks and gloves. Someren et al (Someren et al., 1982) warned by the results of their study that active heating of gloves and footwear in either cold air or cold water may carry the risk of inducing insidious hypothermia. There can also be several types of trouble with electrical heating connected with equipment and activities (Haisman, 1988).

In 1993, over 43,000 reported toe/foot injuries in Sweden were work related (Arbetarskyddsstyrelsen, 1995). Steel enforcements in footwear are aimed at avoiding most of these injuries. Many jobs require additional protection of the toes or shins (safety boots) (Oakley, 1984). However, safety boots are often heavy, bulky and are considered to be "cold", making people less inclined to use them.

Endrusick (Endrusick, 1992) studied different types of boots for the U.S. Navy. He found that if the boots lacked an integrated steel safety toe, the personnel were at a higher risk of severe foot injuries. However, the steel toe cap can restrict fitness and adjustability (Bergquist & Abeysekera, 1994). In a questionnaire survey by Bergquist & Abeysekera (Bergquist & Abeysekera, 1994) the highest reported problem was on footwear thermal comfort (57 %). Of this, 43 % related to discomfort and cold sensation associated with the steel toe cap and it's alleged cooling effect. However, studies have not shown any conclusive effects of the steel toe cap on the thermal properties of the shoe. According to many studies (Bergquist et al., 1997; Elnäs et al., 1985; Påsche et al., 1990) work shoes with steel caps and steel-soles were not thermally different from the same models without steel enforcements.

However, cold injuries in heels and toes are not the most common problems of improper boots for cold environment. Injuries caused by slipping and falling are more frequent (Påsche et al., 1990). The sole must be designed according to the intended use of footwear, to avoid slipping and stumbling, but also to protect from harmful effects of contacting surfaces of various conditions (oil, nails etc.). Chiou et al (Chiou et al., 1996; Rowland, 1997), Rowland (Rowland, 1997) and Gao (Gao, 1999) described some methods for testing slipping and show interesting results.

1.4.3 Effect of sweating on the thermal insulation of the footwear

Often the cold sensation in the feet is connected with low skin temperatures due to sweating and moist feet. The footwear can be well insulated, but when getting wet, whether due to an outside or inside source, the feet start feeling cold. Dry fibres and air between them are good insulators. The problem occurs, when air in and between fibres is replaced by moisture. Water conducts heat about 23 times better than air. The insulation capacity of air does not differ considerably at various humidity levels (the thermal conductivity of water vapour is within the same magnitude range). However, the condensed water replaces air in and between fibres, thus inducing further and faster cooling.

Footwear, especially protective footwear for occupational use, is often made of impermeable or semi-permeable materials. Impermeable materials do not allow the water from the outside to make the insulation wet (Santee et al., 1988). At the same time, in such boots almost all the moisture from sweat condenses inside. In the worst case the sweat production can be higher than the possible water input from outside. The leather footwear can breath to some extent depending on the leather and the type of shoe polish used. The polish and leather treatment protects from outside water, as well. However, long work days in a wet environment and snow can quickly wear off the protective layer. From this point of view the days with changing weather and wet melting snow are the worst (Martini, 1995).

During colder weather (-10 to -30 °C or lower) the water from the outside is generally not a problem, except at certain jobs or activities where water is involved, e.g. fire-fighting or farm work. In cold conditions the condensation of sweat could be the major problem. According to the laws of physics the moisture moves towards the colder surfaces where there is a lower water vapour pressure. Thereby, it is transported by air and the materials away from the feet. However, at a certain distance from heat source, i.e. feet, the humidity condenses and at a certain distance, where the temperature drops under 0 °C, it freezes. Ice in turn conducts heat about 4 times better than water. In this way the footwear insulation is gradually reduced and the feet are exposed to cooling. At lower temperatures the border, where humidity condenses and water freezes, becomes closer to the feet. Ice formation in footwear was reported, for example, during the bandy world championship in Russia (Österberg, 1999). Severe cold (-40 °C) in combination with high sweating rates contributed to this phenomenon. Also, under favourable conditions the condensed water can move back towards the warmer areas by capillary action, creating a circulation for heat transport.

The sweat rate in feet has a clear relationship with foot skin temperature (Rintamäki & Hassi, 1989b). During relatively heavy exercise the average sweat rate can be around 10 g/h/foot (Hagberg et al., 1985; Rintamäki & Hassi, 1989b). Rintamäki and Hassi (Rintamäki & Hassi, 1989b) proposed that the sweat rates during occupational exposure should generally lay around 3-6 g/h. Gran (Gran, 1957) supposed that the sweat rate changes in average from 3 g/h during rest to 15 g/h during hard work. He showed that the foot skin temperatures were connected to the amount of sweat absorbed in various shoe parts, and observed that the biggest humidity concentration was in sole, heel and toe sections.

1.4.4 Footwear design

User involvement in any kind of product development is of critical importance. The effect from user involvement in footwear design is shown by (Rosenblad-

Wallin, 1988) in a study on developing new military boots. A market research on available models can make the design and choice of footwear for special purposes much easier (Perry, 1998).

The feet are special in the sense of heat loss because in normal circumstances only they are in contact with the ground serving as the main or only route of conductive heat loss. Because of the unfavourable mass-surface area relationship of the feet and a lack of a large mass of muscles, the feet are susceptible to loosing heat but are unable to produce it in large amounts (Rintamäki et al., 1992).

There are many conflicting requirements for ideal footwear design, such as mobility, protection, insulation, waterproofing, vapour permeability, durability, weight, fit etc. (Oakley, 1984). Safety shoes that are worn in the cold climate have to protect from work hazards and at the same time offer thermal comfort to the wearer (Bergquist & Abeysekera, 1994). The total foot comfort is determined by the interaction between socks, soles and shoes. The shoe should fit well on the foot. It should be large enough for socks and allow the toes to move (Nielsen, 1991). Fitness, thermal comfort, protection from work hazards, low weight and anti-slip are most important when designing safety shoes for cold climate (Bergquist & Abeysekera, 1994).

Complains of cold feet during occupational and leisure-time cold exposure are well-known. Relevant information on cold protective properties, e.g. insulation, can help the user in the selection of footwear. However, the European Standard for footwear testing (EN-344, 1992) and its labelling system do not require the insulation value for footwear.

Important factors for feet temperatures are the insulation of the shoe and the extent to which blood circulation to the feet is being affected (Påsche et al., 1990). The insulation properties of shoes to a great extent depend on the amount of air trapped inside the fabric and between the foot and the shoe. In cold climate, it is important that the shoes are big enough to accommodate the thick socks (Bergquist & Abeysekera, 1994). Compression of insulation layers must be avoided if possible. Attempting to increase the insulation by increasing the number of socks may not be very efficient - e.g. stuffing two pairs of socks into a boot designed for one pair squeezes out insulative air and substitutes for conducting fibre. At the same time compression of the foot can occur and this reduces the circulatory heat delivered to it (Påsche et al., 1990).

Footwear must possess good thermal insulation. Thermal comfort of feet does not depend only on insulation of footwear, but also on the humidity level in them, footwear material, activity, foot cleanliness etc. The sweat secreted by feet should not condense inside the boots in disturbing amounts. Footwear should be able to protect the feet from wetting due to environmental moisture (Rintamäki & Hassi, 1989b). Dampness of the fabrics leads to impaired insulation properties. During walking or other activities where feet are involved the air moves in footwear. The so-called pumping effect is a good way to get rid of water vapour. The shoe must be designed in a way that it allows the pumping effect (Bergquist & Abeysekera, 1994). In ordinary shoes the pumping effect removes about 40 % of the humidity (Gran, 1957). In the case of winter boots, however, the pumping of moist air during walking is minimal (Rintamäki & Hassi, 1989b).

Weight is another important factor for choosing footwear. Several studies have shown that increase in weight of footwear for 100 g will increase oxygen consumption for about 0.7-1.0% (Frederick, 1984; Jones et al., 1986; Jones et al., 1984; Legg et al., 1986). The weight added to footwear is equivalent, in energy cost, to about five and more times the weight carried on the torso (Legg & Mahanty, 1986; Oakley, 1984).

The other factors for choosing footwear can be colour and reflectance, which can have an effect on heat load. The dark colours customarily chosen for boots absorb the most incident radiation, so that when there is positive net radiation they will be the warmest (Clark et al., 1978; Oakley, 1984).

1.5 Test methods for determining insulation values of garments and footwear

Various indirect methods can be used for determining the insulation of garments. One way is to measure the heat and vapour transfer properties of textiles (EN-31092, 1993) and later estimate the insulation and evaporative resistance by mathematical calculations.

Another possibility for estimating thermal properties is to measure the rate of the change in temperature inside of a product after moving it from one environmental condition to another. This is done in such way by the present standard for testing footwear (EN-344, 1992). A sensor is fixed to the innersole and the footwear is filled with steel-balls (∅ 5 mm, 4 kg). The temperature change of 10 °C within 30 minutes at a gradient of 40 °C (from +20 to -20) is the criterion for passing the test. The standard does not provide a method for estimating insulation. Also, the test is related mainly to the sole area. The sole insulation is an important factor for the cold protection of feet, however, the standard test method for determining the thermal properties of footwear (EN-344, 1992) does not provide sufficient feedback on the weak points in the footwear construction to the manufacturers.

By a former Soviet Standard for footwear testing (GOST-12.4.104-81, 1981) a calculation of the insulation was required. It measured the temperature change of water filled rubber balloons that are shaped as a last for footwear manufacturing. Empirical formulas were used to calculate the insulation of the footwear from the time that has been required to reduce the water temperature for 5 K. Insulation calculation for separate zones (soles, toes) was not dealt with. However, that standard is not in use any more.

Thermal insulation of separate clothing pieces or garment ensembles is possible to measure on humans (GOST-12.4.185-96, 1996). By this Russian standard the subject has to be at thermal comfort during the tests, and the heat losses and skin temperatures are recorded at 11 spots on the body. Based on the heat losses, skin and ambient temperatures it is possible to calculate the insulation value for garments. The same method has been used in several studies (Ducharme et al., 1998a; Ducharme et al., 1998b).

Similar measuring principles are used while testing garments on thermal models/manikins. Recorded heat losses through garments at constant environmental and model surface temperatures allow to calculate the insulation value of a garment. These principles are used for evaluation of gloves (EN-511, 1993) and clothing (ENV-342, 1997). However, the values from human and manikin tests are not always the same (Ducharme & Brooks, 1998a; Ducharme et al., 1998b). The reasons for the discrepancies are still unclear.

Besides the evaluation of the clothing, the acquired insulation values allow to calculate the skin temperature or recommended exposure time in cold according to various mathematical and prediction models (ISO/TR-11079, 1993). Lotens (Lotens, 1989; Lotens et al., 1989a; Lotens et al., 1989b) has presented a model for simulation of foot temperature. The model includes factors such as blood flow to feet, thermal insulation of footwear, and environmental climatic conditions.

There are whole body thermal models/manikins available for evaluation of climatic conditions and clothing (Holmér et al., 1995a; Holmér et al., 1995b; Meinander, 1992b). However, thermal manikins are used also for other purposes. The construction of thermal manikins varies and depends on their use (Nilsson et al., 1999). Because of various reasons it is quite hard to divide whole body manikin into ultimate number of zones and often there is no need for that. However, sometimes a more exact evaluation of various local areas is needed. Hand (Nilsson et al., 1992), head (Liu et al., 1996) and foot (Bergquist & Holmér, 1997) models of this type have been developed.

Several thermal manikins that allow to simulate sweating are available or under construction for this reason (Giblo et al., 1998; Meinander, 1992a; Weder, 1997). Also, similar thermal models on some particular body parts are available, for example, head, hand and foot (Burke, 1998a; Kuklane et al., 1997c; Liu et al., 1997; Uedelhoven et al., 1998).

Measurements on walking thermal manikin have shown considerable effect from air velocity and motion (Holmér et al., 1999). Dynamic tests have been carried out on foot model, too (Bergquist & Holmér, 1997). The motion reduces the insulation around 10-25 %. The effects of wetting of the insulation can be even higher. Tests of immersion (Santee & Endrusick, 1988) have been carried out with thermal foot model and the reduction of insulation could reach to about 40 %.

Various sweating systems are in use. A thermal manikin Coppelius (Meinander, 1992a) uses a microporous membrane that transmits water only in vapour form. (Liu & Holmér, 1997) used cotton skin on model surface. The water was distributed in liquid form. It evaporated from the cotton surface or was transported further by clothing fibres. This method allows to simulate sweating also on ordinary thermal models when tubing is added to transport water and a material is added as skin for water distribution (Mahmoud, 1997). The latest models are using a heat pipe construction with a porous metallized skin (Giblo et al., 1998).

Some studies have been carried out with thermal foot models (Bergquist & Holmér, 1997; Elnäs et al., 1985; Santee & Endrusick, 1988). Santee and Endrusick (Santee & Endrusick, 1988) tested footwear insulation reduction due to the outside source (immersion). Some work has been done with the simulation of sweating (Uedelhoven & Kurz, 1998).

The thermal foot model method has been used by commercial companies and defence research establishments to test and evaluate the footwear, however, most of that information is not broadly available (Burke, 1998b; Uedelhoven, 1994; Uedelhoven, 1998). Comparative studies between laboratories and different foot models are also rare.

2. Aims and objectives

Cold feet and toes are common problems at various jobs and activities. The results of a questionnaire survey showed that the demand for *thermal comfort* of cold weather safety shoes was ranked second after *fitness* and before *protection from work hazards* (Bergquist & Abeysekera, 1994). Therefore, it is important to choose shoes with proper insulation properties for various jobs. Thermal comfort of feet does not depend only on insulation of footwear, but also on humidity level in the boots, boot material, activity etc. A good method for measuring footwear thermal insulation is thus needed.

The method should give information on the thermal protection of the footwear, feedback to the manufacturers on footwear thermal performance in general, and if possible, also on different parts. The method should be able to relate the acquired information to the actual wear conditions for end-users. The results should be possible to be used in mathematical models for the choice of footwear and recommended exposure times. The present standard method (EN-344, 1992) does not allow all that.

Further, a validation of the method on human subjects is needed. Both laboratory tests and field surveys should give the relevant basis for the evaluation and validation of the method. The research projects should study the problems with cold as well as suggest improvements or introduce available solutions to the broader public.

The steel toe cap and its alleged cooling effect has been a frequent subject of complaint. However, previous studies have not pointed out any effect of the toe cap on the thermal properties of the shoe (Bergquist & Holmér, 1997; Påsche et al., 1990). The only difference that has been established is that the time for re-warming the foot when going inside is a bit longer when wearing shoes with steel toe cap (Arbetshygienskainstitutet, 1982).

The aims and objectives of the research study were to:

- Evaluate and improve a thermal model method for testing of footwear by comparing of insulation values of various cold weather footwear.
- Analyse the effects on thermal insulation of wetting of the footwear from the inside. Determine how the footwear insulation could change at various sweat rates and to find out the relationship for insulation changes. Study the short and long term effects of sweating on footwear insulation, as well as the effect of motion.
- Determine the effects of various insulation levels on foot skin temperature changes during low activity work in cold environments.
- Compare the methods of determining the footwear insulation on human subjects and the thermal foot model in order to evaluate the use of the model data in practice and in mathematical models.
- Validate the predictions with a mathematical model using actual measurements on subjects exposed to cold environments and the insulation values measured on the thermal foot model.

- Improve the basis for an alternative test method instead of the present standard (EN 344) for determining the thermal properties of cold weather footwear and propose the change of the standard method.
- Develop recommendations on footwear use based on the measured insulation and human activity during work in cold.
- Find out the trends and the need for further research in this particular area.

3. Methodology

The research consisted of measurements on thermal foot models (Table 1), tests with human subjects (Table 2) in laboratory and field studies.

3.1 Instrumentation

3.1.1 Thermal foot models

Two thermal foot models were used in the course of the research series for measuring heat loss through footwear. An older model (F2) was used during the first tests and newer one (F3) for the other tests. The new model was made during the study series. It differs from its predecessor by the number of zones, and joint motion. F2 had 9 zones versus 8 zones on F3. F2 has a movable joint only at toes while F3 can be moved at toe and ankle joints. Thanks to the flexion at ankle it is possible to push F3 into the proper size (40-41) of footwear. The length of the foot of F3 is 254 mm and width 86 mm versus 263 and 87 mm of F2.

The main improvement of F3 is that it has 3 in-built “sweat glands”. They are located on the top of the toe zone, under the sole at the border of heel and sole zones, and on the medial side of the ankle zone. The new model's surface is totally covered with tape to restrict the water from reaching the measuring wires and causing short-circuit, while the old model has the tape only on measuring wires. The total volume and areas of the models are about the same.

Both models are working on the same principles. The main principles are to keep certain variables constant, e.g. surface temperature of the model and environmental temperature, and by changing other parameters, e.g. clothing, measure the difference in third parameters, e.g. power input. Power input is proportional to the heat loss. Further calculations give insulation values of footwear. The regulation program for thermal models developed at the National Institute for Working Life (NIWL) allows to choose a constant surface temperature, a constant heat loss or physiological temperature. However, most commonly constant surface temperature is used. 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. The ambient temperature should be chosen to be at least 20 °C lower than the surface temperature of the model (usually more than 30 °C) to guarantee enough big temperature gradient and heat losses in order to reduce the measuring error. According to the recommendation the surface temperature of the foot model was usually kept at 34 °C. The calculations can be carried out for each zone separately, for zone groups and/or for whole model:

Table 1. Overview of the studies with thermal foot model. The ordinary test length was 90 minutes if not stated otherwise.

Study	Surface temperature (°C)	Ambient air temperature (°C)	Boots	Socks	Use of weight	Sweating	Motion	Comments
Paper I	34	-20 and -10	WS, WN, model 515 (similar to VS and VN)	Bare foot, thick (34 g/sock)	No weight, 10 kg	No sweat	No	Measurements of heat loss change rate in a special test
Paper III	34	+3	BS, BN, AS, AN, VS, VN, WS, WN	Bare foot, thick (34 g/sock), thin (20 g/sock)	No weight, 35 kg	No sweat, 10 g/h	No	
Paper IV	34	+2	BS, AS, VS, WS, SM	Thin (20 g/sock)	35 kg	No sweat, 3, 5 and 10 g/h	No	Additional tests with 5 g/h sweating: 12-hour test and test at 34 °C
Paper V	34	+4	BN, VS, WS	Thin (20 g/sock)	Dynamic	No sweat, 10 g/h	Walking on treadmill 4 km/h	
Paper VI	30	-10 -20	WS, WN SG, SM	Thin (20 g/sock)	Dynamic	5 g/h	Up-down motion at 8 steps/min	One week test (5 days use), wind 1.5 m/s

Table 2. Overview of the studies on subjects.

Study	Subjects	Subjects' data mean (range)	Activities and environmental conditions	The used footwear
Paper I (a laboratory study)	6 males	33 (27-43) years 174 (167-186) cm 79 (71-86) kg	Sitting, 30 min at 19 °C, 60 min at -10 °C, 30 min at 19 °C. Each subject had to perform the test twice.	The boots were mixed so that three subjects wore WS and three wore WN on their right foot during their first trial. The second trial was just the opposite.
Paper II (a laboratory study)	8 males	32 (25-42) years 174 (168-184) cm 75 (62-86) kg	+3, -12 and -25 °C, sitting or standing, 60 min in cold (from 20 to 30 min walking), 20 min at 23 °C, 25 min in cold, 15 min at 23 °C.	WS and WN at -12 and -25 °, BS at +3 and -12 °C, AN at -12 °C, AS at +3, -12 and -25 °C
A field study at a harbour	8 males	31-62 years 180 (170-187) cm 89 (70-104) kg	Daily activities for 4 jobs: cutting asphalt, fastening steel to platforms, fastening paper to platforms and signalling during loading the trailers. The mean air temperatures varied from 4.0 to 8.0 °C (min 0.3 °C) and wind from 0.14 to 3.7 m/s (max 11.6 m/s)	Seven subjects used WS and one used shoes. The use of socks varied.
A field study on high masts	8 males	40 (22-50) years 177 (173-184) cm 87 (72-105) kg	Daily activities for jobs on masts, mean ambient air temperature ranged from -0.8 to -10.2 °C (min -13.0 °C) over the days and mean wind speed from 1.7 to 9.7 m/s (max 13.5 m/s)	Six subjects used WS, one used Arbesko boot model 529 and one used Graninge boots. The use of socks varied.
Paper VII (a field study)	17 males and 3 females	42 (19-68) years 179 (160-193) cm 84 (58-115) kg	Daily activities in milking farms: milking, clearing dung, feeding animals etc. The mean air temperatures varied from 1.7 to 18.9 °C (min -10.8 °C).	Most of subjects used the rubber boots, 2 wore shoes part of the time and 2 had other boots (Graninge and Sherpa). The use of socks varied.
Paper VIII (a laboratory study)	2 males and 4 females	45 (30-66) years 166 (156-173) cm 72 (57-86) kg	Heat losses and skin temperatures were measured in eleven points on bare foot of sitting subjects at 23, 18 and 13 °C and with footwear at 19.5 and 13 °C.	Boots WS, AS and BS were measured on 2 subjects.

$$Q_i = \frac{P_i}{A_i} \tag{1}$$

$$I_{t,ri} = \frac{T_i - T_a}{Q_i} \tag{2}$$

$$I_{t,r} = \frac{\overline{T}_s - T_a}{\sum P_i \big/ \sum A_i} \tag{3}$$

where 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); $I_{t,r\,i}$ - insulation of a zone (m^2°C/W); $I_{t,r}$ - total insulation (m^2°C/W). There is available a short description of some other models of this type (Kuklane et al., 1997c).

The heat losses from the models are measured and the insulation values can be calculated for the whole boot as well as for the independent zones. The latter allows the more precise evaluation of footwear. The method is also described by Bergquist & Holmér (Bergquist & Holmér, 1997) and Elnäs et al (Elnäs et al., 1985).

3.1.2 Water pump

A peristaltic pump (Gilson, Inc., Minipuls, 8 channels) was used for water distribution the independent “sweat glands”. The pump allows flow rates from 0.05 ml/min to 40 ml/min. In the study series the sweat rates of 3, 5 and 10 g/h were used. The PVC-tubing for water transport was insulated and heated to ensure the appropriate water temperature when entering the foot model. The heating was regulated with a computer program.

3.1.3 Tests on human subjects

Skin and ambient temperatures were recorded every minute. In the laboratory the temperatures were measured with NTC-resistance, temperature matched thermistors manufactured according to Mil-T-23648 (Rhopoint Components Ltd, type ACC). During field studies the StowAway temperature loggers (Onset Computer Corporation, range from -39 to +122 °C, with external sensor, (Fuller et al., 1999)) were used. During the laboratory studies the foot skin temperatures were measured on dorsal foot, lateral heel and second toe. In the field studies the sensors were attached to dorsal foot and second toe.

The scales for thermal, pain and comfort sensations are shown in Table 3. A symmetrical 9-point scale (ISO-10551, 1995) was used for the thermal sensation recording. The subjects were free to tell any thermal and pain response value in between the given scale values at certain intervals.

Table 3. Subjective sensation scales for thermal and pain responses and comfort sensation.

Thermal Responses		Pain Responses		Comfort Sensation	
4	very hot	0	no pain	1	comfortable
3	hot	1	slightly painful	0	neutral
2	warm	2	painful	-1	uncomfortable
1	slightly warm	3	very painful		
0	neither warm nor cool	4	very, very painful		
-1	slightly cool				
-2	cool				
-3	cold				
-4	very cold				

3.1.4 Climatic chambers

The cold chamber used in the study is adjustable from +5 °C to -30 °C. The changes from the set temperature were in the range of ±0.8 °C. Air velocity stayed at 0.23±0.07 m/s. The warm chamber can be adjusted from +5 °C to +40 °C. The changes from the set temperature were less than ±0.25 °C. Air velocity stayed at 0.15±0.05 m/s.

Figure 1. The footwear.

3.1.5 Footwear

The same or similar footwear (Figure 1) have been used throughout the study series. They are described shortly in Table 4 and in more detail in respective papers. The footwear that was used occasionally is described in respective section and paper. During the wet measurements a thin sock (~20 g, 70 % cotton, 30 % polyamide) was always donned on foot model for better water distribution. Each boot had its own sock of the same type. (The slip resistance and wearability of boot WS has been evaluated in a study by Gao (Gao, 1999).)

Table 4. The footwear.

Code	Model	Manufacturer	Notes
BS		Sweden Boots AB, Sweden	Rubber
BN		Sweden Boots AB, Sweden	Like BS, but without steel toe cap, made only for the study
AS	533	Stålex, Arbesko AB, Sweden	Leather
AN	533	Stålex, Arbesko AB, Sweden	Like AS, but without steel toe cap, made only for the study
VS	536	Stålex, Arbesko AB, Sweden	Leather, nylon fur
VN	536	Stålex, Arbesko AB, Sweden	Like VS, but without steel toe cap, made only for the study
WS	520	Stålex, Arbesko AB, Sweden	Woodman, impregnated leather, Thinsulate, nylon fur
WN	520	Stålex, Arbesko AB, Sweden	Like WS, but without steel toe cap, made only for the study
SM	Mukluk	Sorel, Kaufman, Canada	Three layer boot (two inner-boots), rubber, nylon, felt

3.2 Conditions and procedures

A brief description is given below. For more details the reader is referred to original papers.

3.2.1 Thermal effects of steel toe caps in footgear (Paper I)

3.2.1.1 Measurements with the artificial heated foot

Insulation values of the footwear were determined with the thermal foot model (F2) placed on a copper/zinc alloy plate (Table 1). The use of the plate was decided according to the European Standard on footwear testing (EN-344, 1992). Each measurement lasted for about 90 minutes. Data from the last 10 minutes were used to calculate the insulation values. Double determinations were carried out for each case. The allowed difference between double determinations was 0.01 m^2°C/W. If the difference was bigger, then a third test was carried out. A vertical pressure of 10 kg was applied to the thermal foot model to simulate the pressure exerted on the soles by a sitting subject.

Another test was done with the thermal foot model to compare the rate of change of heat loss through the footwear. The thermal foot model was fitted with the boot and exposed to room temperature (19.0±0.5 °C) for 30 minutes. The boot with thermal foot model was then placed under -10 °C for 90 minutes and again kept at room temperature for 1 hour (i.e. altogether 180 minutes). The difference in the drop (120 to 145 min) in heat loss from the toe zone was used to compare the thermal properties of boots with and without steel caps. Measurements with each boot were repeated 3 times.

ANOVA for repeated-measures was used for analysis of insulation values and simple t-test for heat loss change rate.

3.2.1.2 Measurements on subjects

Six male subjects performed the test twice (Table 2). The climate chamber temperature was kept at -10 °C for all the trials. Room temperature outside the climatic chamber was at 19.0±0.5 °C, with a relative humidity of 28±5 %.

Boots WS and WN of appropriate sizes were used by the subjects. The pairs of boots were mixed so that a pair consisted of one WS and one WN. Three subjects wore WS and three wore WN on their right foot during their first trial. The second trial was just the opposite. Socks of the same model were also provided for all the subjects. The subjects were told not to move their legs during the exposure. However, some movement of legs occurred during the tests.

Each trial lasted for 120 minutes, during which the subjects constantly wore the boots. They sat at room temperature when the measurements of skin temperature started. On 30th minutes they moved into the climatic chamber. After 90 minutes of the experiment (60 minutes of cold exposure) the subjects left the climatic chamber. For the next 30 minutes skin temperature recovery was recorded. The metabolic rate could be estimated to be 70-90 W/m^2.

Statistical analysis consisted of t-tests on 5-minute mean skin temperature values. Differences in subjective responses were studied with t-tests, too.

3.2.2 Effect of footwear insulation on thermal responses in the cold (Paper II)

Each subject came 11 times: once for practice and information and 10 times for experiment (Table 2). The clothing was adjusted to the size of the subject and to the different environmental conditions. The insulation values of clothing were measured on a thermal manikin according to (prEN-342, 1995). For +3 °C clothing insulation was 1.95 clo, for -12 °C it was 2.28 clo and for -25 °C 2.55 clo.

The measurements started when a subject entered the climatic chamber. His thermal and pain sensations were recorded during the exposure. During the cold exposure the subjects mainly stood or sat (metabolic rate 80-100 W/m^2). Between 20th and 30th minute of cold exposure they walked on a treadmill at a speed of 5 km/h (metabolic rate around 160 W/m^2). On 60th minute the subject came out from the climatic chamber. The subject stayed in a warm room (23 °C) for 20 minutes. He could open the parka and take off the gloves, but the footwear had to stay on. On 80th minute the subject moved back to the cold chamber and stayed for 25 minutes. On 105th minute he came out from climatic chamber. The subject sat in warm room for 15 minutes. On 120th minute the test was finished. The average metabolic rate during this 2 hour test was estimated to be about 80-95 W/m^2.

For statistical analysis 5 minute average values of skin temperatures and 5 minute differences in skin temperatures, i.e. changes in skin temperature during 5 minutes were used. Analysis of variance (ANOVA) with Fishers PLSD at 0.05 probability level was used. For statistical analysis of subjective responses the same methods were used. Regression between subjective responses and foot skin temperatures was also studied.

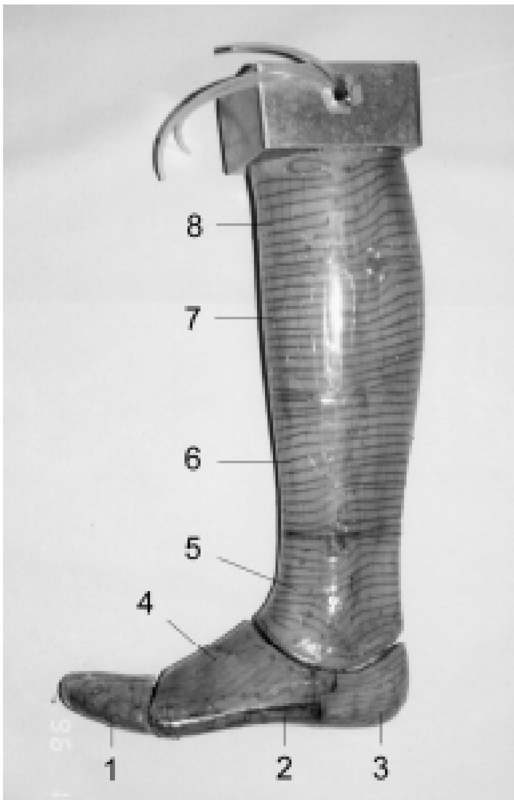

Figure 2. Thermal foot model. Zones: 1 - Toes; 2 - Mid-Sole; 3 - Heel; 4 - Mid-Foot; 5 - Ankle; 6 - Lower Calf; 7 - Mid-Calf; 8 - Guard.

3.2.3 Effect of sweating on insulation of footwear (Paper III)

The tests were carried out under standardised conditions: chamber temperature +3.0±0.5 °C, wind 0.15±0.05 m/s. The foot model (F3, Figure 2) was placed in an upright position on a copper/zinc alloy plate (Figure 3). The duration of each test was 90 minutes and each condition was tested twice. Between the tests the boots were left at room temperature (21±0.5 °C, relative humidity 33±5 %). All the tests were carried out when the foot was standing. Boots of size 41 were used for test (Table 1). The boots were chosen so that a wide range of insulation values could be represented, from rubber boots to heavy winter boots. Six conditions were used for testing the boots (Table 5).

Table 5. Combination of measurement conditions.

Abbreviation	Dry/Wet	Weigh 35 kg	Sock
DNN	Dry	No	No (N)
DW1	Dry	Yes	Thick (1)
DN2	Dry	No	Thin (2)
DW2	Dry	Yes	Thin (2)
WN2	Wet	No	Thin (2)
WW2	Wet	Yes	Thin (2)

In wet condition the water flow was regulated to be 10 g/h. For 90 minute test the total water supply was 15 g. The weight of the boot and sock was measured at the beginning and at the 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. Total insulation was defined as the insulation from toes to ankle.

3.2.4 Change of footwear insulation at various sweating rates (Paper IV)

Five boots of size 41 were tested (Table 1). The footwear was chosen to cover a wide range of insulation levels from thin rubber boot to winter boot for extreme cold. Double determinations were carried out for each boot and condition. The total insulation of the double determinations were not allowed to differ more than 5 % or 0.01 m^2°C/W. If they differed more then a third test was carried out. During the entire test series only one third test was needed.

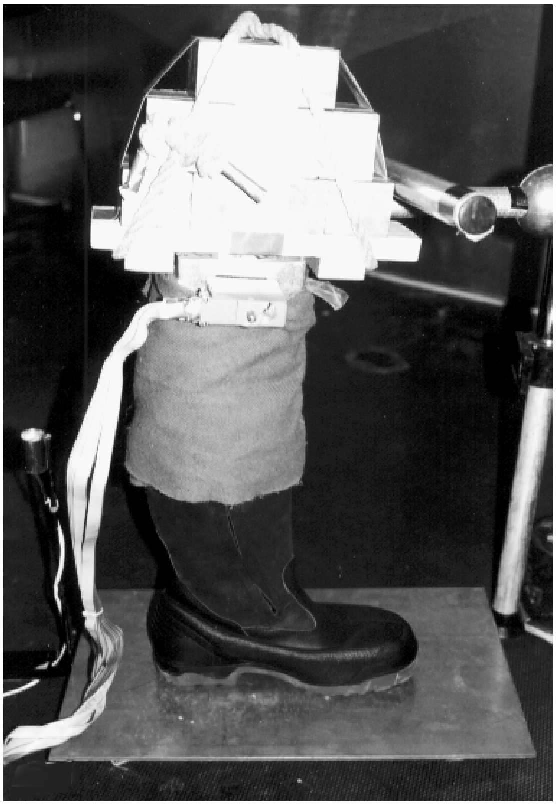

Figure 3. Setup for insulation measurements with thermal foot model.

The environmental conditions during the tests were the following: ambient air temperature was 2.2±0.6 °C, air velocity was 0.23±0.07 m/s at ankle height and air humidity was 75±8 %. The footwear was conditioned at 19.1±0.7 °C and 38±5 % relative humidity. The conditioning time varied. For the first test, it was around 1 week, and for the second around 2 days depending on the criteria of reaching the initial dry weight. The weight of the footwear was recorded before and after each test. The sock and the footwear were weighted separately.

In addition, a long wet test (8-hour sweating) and a test at 34 °C were carried out with some boots. Both tests were done with a flow rate of 5 g/h. The first test was carried out to observe the insulation change over 8 hours. The second test was to estimate the evaporative heat losses.

During the long tests the environmental conditions were the same as during the tests at various sweating rates. The weight was not used. Two “sweat glands” were added for more even water distribution: one on top of dorsal foot (mid-foot zone) and the other to lateral ankle. The test lasted for 12 hours: 1 hour to stabilise the heat losses in the beginning of the test, 8 hours for wet tests and 3 hours for dry test in the end. Footwear was weighed before the test, after 8 hours of wet measurements and at the end. Some disturbances occurred in measurements due to the footwear doffing and donning for weighing in the beginning of 3-hour dry test. After 6 hours of sweating the heat losses from the rubber boot (BS) were so big that the continuation of wet test was not possible. In this case the 3-hour dry test was continued from that time point.

Finally, a test where the ambient temperature and the surface temperature were equal (34.0±0.2 °C) was carried out in a warm chamber. The relative humidity in the chamber was 28±1 %. The idea for the test came from the study by Liu & Holmér (Liu & Holmér, 1997). Weight was not used during these tests. Even in this test 5 “sweat glands” were used.

3.2.5 Reduction of footwear insulation due to walking and sweating (Paper V)

The measurement setup for walking is shown in Figure 4. Two pneumatic pistons were used to move the foot. Walking speed (step rate) was adjusted to 4 km/h after the treadmill velocity.

Water was supplied to three “sweat glands” at the rate of 10 g/h (Table 1). The total insulation was calculated on the bases of the insulation of toe, sole, heel, mid-foot and ankle zones.

3.2.6 One week sweating simulation test with a thermal foot model (Paper VI)

Five “sweat glands” (3 built-in and 2 external made of PVC tubing) were used for water supply. Boots WS, WN, SM and SG were tested (Table 1). SG was an extra warm footwear consisting of 2 layers: outer shell of nylon with an insulation layer, and a felt inner-boot.

Each boot was tested for 5 days. Each day was divided into 9 hour measurement period and 15 hour conditioning period. Boots WS and WN were measured at -10.7±0.9 °C and conditioned at room temperature (20.1±0.5 °C, RH 39±6 %). SG was measured at -20.8±1.0 °C and conditioned in a refrigerator (simulating a temperature in a tent) at -5.0±0.8 °C (RH 35±6 %). Two series were carried out with SM. In first series it was conditioned in an insulated box in cold chamber and in second in the refrigerator. However, in the first series the cold chamber warmed up during night according to its working regime and the average conditioning temperature was 0.9±4.1 °C (RH 78±6 %). In here the tests with SM were carried out at -18.7±0.8 °C. During second series it was measured at -20.8±0.9 °C conditioned at 2.8±0.6 °C (RH 44±9 %). The inner-boots and insoles of SG and SM were taken out over night. It should be noted that the refrigerator had a relatively good air circulation inside, and the air humidity reduced from about 70 % to 40 % within 2-3 hours, while the relative humidity in the box increased and stayed for most of the time at about 80 %. In the end of the fifth measuring day the boots SG and SM were left at the room temperature (21.7±0.5 °C, 48±2 %).

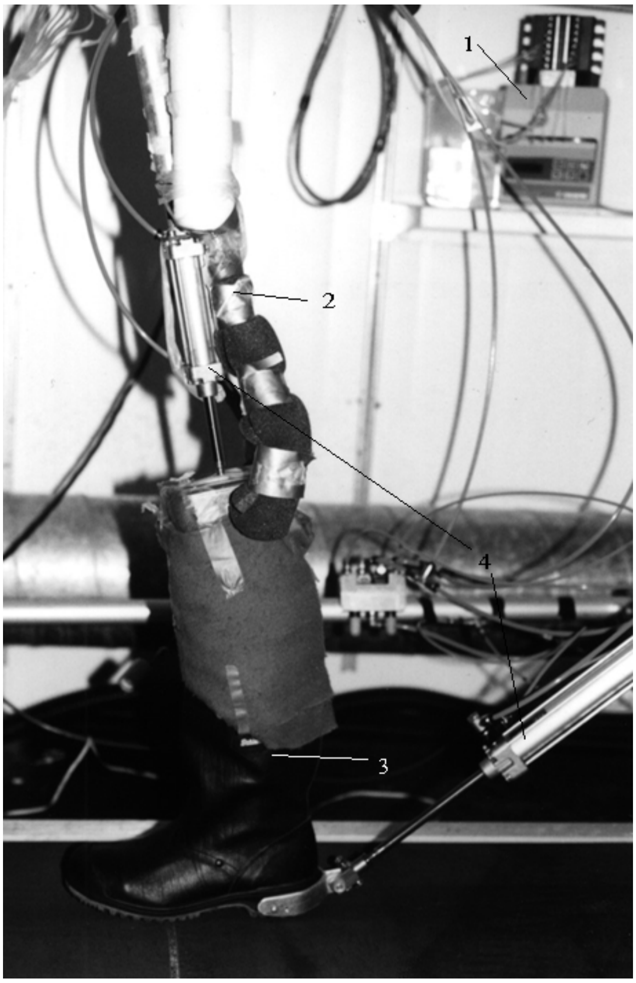

Figure 4. Setup for walking tests. 1 - peristaltic pump; 2 - insulated and heated water tubes; 3 - foot model clad in boot; 4 - pneumatic pistons.

The first measuring hour was without sweat simulation. During that time the heat losses stabilised and the start insulation of the day was calculated based on the last 10 minutes of that hour. During the following 8 hours the water was supplied at a rate of 5 g/h. The pump and water supply were located in an insulated box and water was transported in an insulated and heated tubing. Footwear was weighed in the beginning and end of each measurement day. The footwear insulation was calculated based on last 10 minutes of each half an hour.

To simulate the real wear situation better an up-down motion at 8 steps per minute was simulated with the help of pneumatic system. However, at -20 °C the system had trouble and sometimes stopped working, probably due to the moisture freezing in the system. Wind from front of 1.5±0.5 m/s (measured at ankle level) was applied. The surface temperature of the foot was kept at 30 °C.

3.2.7 Questionnaire survey

A preliminary questionnaire was sent out to various companies. That questionnaire was intended to get to know if the workers were exposed to cold and if they were interested to take part in a more deep study of problems with cold work. A harbour, a telecommunication company and a customs office answered positively and to them was sent a thorough questionnaire (Gavhed et al., 1999b). Thirty questions were directly related to feet and/or footwear. The companies showed interest for continuation of the study and as the first step a field study was planned at the harbour.

3.2.8 A field study at a harbour

The study was carried out in February, 1998 (Gavhed et al., 1999b). February is usually one of the coldest months. However, on the measuring week the weather happened to be relatively warm and calm.

The workers were chosen out among volunteers who carried out 4 different jobs in teams of 2 men (Table 2). Two persons (construction workers) were cutting asphalt (oxygen consumption (VO_2) 0.91 and 0.94 l/min), 2 were fastening steel to platforms for loading to ships (VO_2 1.23 and 1.35 l/min), 2 were fastening paper to platforms for loading to ships (VO_2 0.95 and 1.30 l/min) and 2 were signalling during loading the trailers to the ships (VO_2 0.85 and 1.29 l/min).

The mean air temperature, globe temperature, wind velocity and relative humidity for each job and day were following: cutting asphalt 4.0 °C, 7.6 °C, 2.5 m/s (max 5.2 m/s), 56 %, fastening steel to platforms 7.3 °C, 8.6 °C, 3.7 m/s (max 11.6 m/s), 70 %, fastening paper to platforms 6.7 °C, 7.3 °C, 0.14 m/s (max 0.3 m/s), 68 % and signalling during loading the trailers 8.0 °C, 0.6 m/s (max 2.5 m/s), 79 %.

The workers could choose clothing of their personal choice from the company's store. All the clothes were weighted separately in the beginning and at the end of the workday. The clothing was manufactured by Fristads AB and Taiga AB. The boots were provided by experimenters and they were model 520 (WS, 0.34 m^2°C/W (Paper III)) that were manufactured by Stålex, Arbesko Gruppen AB. As the sizes 45 and bigger were not present, one subject used his own footwear. His shoes were the model 732 from the same manufacturer. The shoes were without warm lining. The insulation of the shoe was estimated to around 0.23 m^2°C/W. Two types of socks were in use: A. 67 % wool, 26 % nylon and 7 % lycra (Arbesko, model 106), B. 80 % cotton, 20 % stretch. Subjects 1-5 used sock A. The rest used sock B. Both types weighed around 75 g/pair.

The workers were observed during the whole workday. Their subjective responses on thermal sensation were recorded and at the end of the day they filled in a questionnaire on that particular day (Gavhed et al., 1999b). Four questions were directly related to feet and/or footwear.

3.2.9 A field study at a telecommunication company

The study was carried out in February, 1999 (Gavhed et al., 1999a). The workers were chosen out among volunteers who carried out various jobs on high masts on

4 different days (Table 2). The work was done in teams of 2 men at 4 different masts in Northern- and Middle-Sweden. A short period of time (10-20 minutes) was used to measure oxygen consumption (VO_2) during climbing the masts. The average VO_2 during climbing was 2.45 l/min (1.18-3.33 l/min). The average VO_2 during the work periods over whole workday was estimated to lay around 0.74 l/min (0.64-0.86 l/min).

The length of the cold exposure depended on the task. The shortest total work time in cold on the mast was on the third day (*Day 3,* changing a warning light): 2 hours 40 minutes. At the same time it was one of the longest cold exposures. The longest total work time in cold was on the second day (*Day 2*, fastening new cables to the mast, half time operating in a mast elevator): 4 hours and 55 minutes (length of a whole work day 6.5 hours). It was divided into two work periods. The longest work day was 7 hours and 30 minutes (*Day 4* mounting up two new parabolas). 4 hours and 30 minutes of that was work outdoors near or on the mast. This day was divided into 4 work periods in cold. The first day (*Day 1*, fastening new cables and taking down old) was 5 hours 40 minutes long and 4 hours of that was spent on or near the mast. The work outdoors was divided into two periods. The time to drive to the mast, preparation for the measurements and ending the measurements were not included above.

The mean outside air temperature (measured near body) and wind velocity for each day were for *Day 1* -7.8 °C (minimum -10.9 °C), 3.4 m/s (max 9.1 m/s), *Day 2* -2.5 °C (minimum -13.0 °C), 3.6 m/s (max 6.1 m/s), *Day 3* -2.1 °C (minimum -2.4 °C), 9.7 m/s (max 13.5 m/s) and *Day 4* -2.1 °C (minimum -5.6 °C), 1.7 m/s (max 4.6 m/s).

The workers used their ordinary clothing. Standard (company recommended) clothing were Ullfrotté underwear and outer layer by Taiga. All the clothes were weighted separately in the beginning and at the end of the workday. During the breaks the workers usually changed footwear and clothing.

Subjects 1-4, 7 and 8 had boots of model 520 (WS) that were manufactured by Stålex, Arbesko Gruppen AB. Subject 5 used Graninge boots and subject 6 model 529 (Varm-varm, Stålex, Arbesko Gruppen AB). The mean weight of the footwear was 1842 g. The weight depended on size - 1681 g for size 40 and 1988 g for size 44. The insulation of WS (size 41) was measured on a thermal foot model (Paper III). The insulation when standing dry with a load of 35 kg and a sock (34 g) was 0.34 m^2°C/W. The insulation of the other boots was estimated to be at the same insulation level, i.e. between 0.33 and 0.35 m^2°C/W.

The workers used two pairs of socks (thin and thick), except subject 6 who used 1 pair of thin cotton socks. Usually various Ullfrotté socks (wool) were used, but also cotton, fibre-fur and synthetic socks were in use, mostly in pair with a woollen sock. By the weight could socks be divided into three groups: thin with mean weight of 69 g (54-82 g), thick 104 g (100-107 g) and extra thick 147 g (133-165 g) per pair. The socks could add about 0.02-0.05 m^2°C/W to the insulation.

The workers were observed during the whole workday. Their subjective responses on thermal sensation were recorded over the day and at the end of the day they filled in a questionnaire about the work day. Four questions were directly related to feet and/or footwear.

3.2.10 A field study in dairy farms (Paper VII)

The study was carried out from January to March in Uppsala area and Västerbotten County, Sweden. Thirteen (13) dairy-farms were visited and 20 farm-workers were studied (Table 2). The workers were chosen out among volunteers who carried out various jobs in milk-production. 15 subjects worked at cold loose housing barns (9 farms).

Temperature sensors (StowAway temperature loggers) were taped to the second toe and dorsal foot. Four workers were studied for the whole workday. The other workers were observed during the morning milking period only. The subjective responses on thermal sensation and activities of all subjects over their work periods were recorded in an observation sheet, and at the end of the day they filled in a questionnaire on that particular day.

Five (5) workers were only milking cows. Ten (10) workers milked cows and did the other jobs, too. The other 5 farm workers cleared dung, worked with fodder and other animal care. Within 20 minutes during the work activities the oxygen consumption (VO_2) was measured on 8 subjects. The mean value for the variety of activities was 1.03 l/min (0.40-1.96).

The workers used their ordinary clothing. The socks and boots were weighted separately in the beginning and at the end of the measured work period. Most of the workers wore rubber boots (16 persons). Usually the rubber boots did not have an insulation layer. Two wore shoes during milking and changed to rubber boots only when cleaning the floor with water. The reason for not wearing rubber boots was reported to be poor air permeability, sweating, coldness and skin disease. One wore insulated leather boots (Graninge) and one insulated scooter boots (Sherpa). The insulation of the rubber boots was estimated to lay about 0.20 $m^2°C/W$ (estimated range 0.19-0.23 $m^2°C/W$), shoes about 0.23 $m^2°C/W$, and Graninge and Sherpa boot about 0.32 $m^2°C/W$ (Paper III). The type of socks varied. Most common were cotton socks. The other types of socks were woollen, synthetic and fibre-pile. Some workers used two pairs of socks. The thin socks used weighted on average 70 g and thick ones on average 140 g per pair. The use of socks can increase the footwear insulation by 0.02 - 0.05 $m^2°C/W$ depending on the type of socks, the initial insulation of the footwear and the footwear size.

3.2.11 Comparative study of 2 thermal foot models

After finishing the new model (F3), a small comparative study was carried out (Kuklane, 1997). The new data measured with F2 and F3, and the data from a previous study (Kuklane, 1995; Paper I) were analysed. The procedure was tried to keep as close to the previous study as possible. The same calculation methods were used.

3.2.12 Determination of heat loss from the feet and insulation of the footwear (Paper VIII)

The tests were carried out on naked foot at 3 environmental temperatures (Table 2). At 23 °C were measured all 6 subjects, at 18 °C four of them and at 13 °C two persons.

Eleven heat flow and temperature sensors, with thickness 3 mm and area 1.8 cm^2 (GOST-12.4.185-96, 1996), were attached to the foot (Table 6). Air temperature was measured with a mercury thermometer. During the measurements on the naked foot the leg was supported by a chair at a calf region so that the foot was hanging in the air. The subjects sat in such a position for one hour. The general thermal sensation of the subjects 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 10^{th} minute. The average of 40^{th}, 50^{th} and 60^{th} minute heat loss and the last skin temperature value were used in the insulation calculation.

Table 6. The measurement points on 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

In continuation, three types of footwear (WS, AS, BS) were tested on two subjects by the same method. One subject used footwear of size 41 and another the 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 naked foot except that this time the soles were supported on floor while the subject was seated. These tests were carried out at 13 and 19.5 °C. A footwear of the size 41 was tested on the model (Paper III). The air layer insulation values measured on naked foot were acquired while model was standing upside down, i.e. sole up.

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

3.2.13 A comparison of two methods of determining thermal properties of footwear (Paper IX)

3.2.13.1 Thermal foot method
The comparison was made with six boots: BS, BN, AS, VS, WS and WN. In the chosen trial the thermal foot model did not have any sock on it, the test was carried out without sweating nor weight. After the footwear was donned, the thermal foot model was placed in a cold chamber on a copper/zinc plate (similar to the EN 344) for 90 minutes. The heat loss data from the last 10 minutes of cold exposure was used for the insulation calculation. All data were obtained in special investigation and have been reported (Paper III).

3.2.13.2 European Standard EN 344
The standard (EN-344, 1992) deals with all tests that are required for evaluating various occupational footwear. The method of determination of insulation against cold (section 5.9) was used for the comparison:

- The test pieces were conditioned 7 days at 20±2 °C and 65 % relative humidity.
- A specified thermocouple was fixed to the insole.
- A heat transfer medium consisting of 4 kg 5 mm steel balls were poured into the footwear.
- After the temperature of the outsole became constant at 20±2 °C, the test piece was placed on a copper/zinc plate into the cold box with an environmental temperature of -20±2 °C for 30 minutes.
- The temperature decrease was recorded and calculated to the nearest 0.5 °C.

If the temperature drop did not exceed 10 °C then a footwear passed a test and is proper for use in cold.

The conditioning was carried out at 2 humidity conditions. The first test series were done according to the standard at 64.7±0.7 % relative humidity (RH). For the second series the humidity was kept at 35.8±0.9 % that is a common indoor humidity during winter time in Nordic countries.

During the tests the standard method was modified to available conditions. Instead of cold box a cold chamber was used and on top of footwear upper edge (collar) was placed a thermal insulating cover with an elongated hole according to the standard. During the standard tests the cold chamber was at -19.3±0.2 °C and the warm chamber was at 20.0±0.1 °C (temperature gradient 39.3 °C). During second series with conditioning at low humidity the cold chamber was at -20.3±0.4 °C and the warm chamber was at 19.6±0.1 °C (temperature gradient 39.9 °C).

In addition, two more tests were carried out according to the standard. One with a boot with low insulation (BS) and one with a boot with high insulation (WS). For BS (BS2) the temperature gradient was adjusted to minimum (36.8 °C) within the allowed temperature limits (conditioning 18.5±0.2 °C, test -18.3±0.3 °C). For WS (WS3) the temperature gradient was adjusted to maximum (42.1 °C) within allowed temperature limits (conditioning 21.5±0.2 °C, test -20.6±0.2 °C).

3.2.14 Validation of a model for prediction of skin temperatures in footwear (Paper X)

3.2.14.1 Thermal foot model

The footwear insulation of boots of size 41 was measured on a thermal foot model (Papers I and III). The same type of sock, that the subjects used, was used on the thermal model.

3.2.14.2 Studies on subjects

The studies on subjects were carried out earlier (Papers I and II). In *Paper I* six male subjects wearing insulated winter boots (WS), were exposed to -10.7 °C. During the cold exposure the subjects were sitting and carrying out some light manual tasks at given intervals. The metabolic rate could be estimated to be 70-90 W/m^2.

In *Paper II* eight male subjects were exposed to 3 environmental temperatures (T_a): +2.8 °C, -11.8 °C and -24.6 °C, using 3 types of footwear: BS, AS, WS (a newer version of boot WS that was used in *Paper I*). During the cold exposure the subjects mainly stood or sat (metabolic rate 80-100 W/m^2). Between 20th and 30th minute of cold exposure they walked on a treadmill at a speed of 5 km/h (metabolic rate around 160 W/m^2).

The average dorsal foot skin temperatures of 1 hour cold exposure and 20 minutes of recovery at room temperature of all subjects from both trials were used for comparison of measured and predicted values. The measured shoulder skin temperature was used to estimate the mean skin temperature.

3.2.14.3 Lotens' foot model

Lotens' model accounts for changing skin blood flow, that depends on temperature and is the most important factor for foot skin temperature change. It also assumes a nutritional blood flow that stays relatively constant. It is based on the presumed principles (Lotens, 1989; Lotens et al., 1989b):

- The extremity consists of a few mm thick skin with blood flow control and thermally passive core.
- The skin blood flow control function (x) is a linear combination of body core and skin temperature and local skin temperature with weights of 1.5, 0.2 and 0.16 respectively, and with a constant that can be interpreted as a sum of threshold values for each factor.
- Skin blood flow (SBF) is expressed as a power function of the control value (SBF=2^x).
- The efficiency for heat transport by blood is 60 % due to counter-current effects.

The model takes into consideration boot and foot size, boot insulation and weight. Some computer program input data for the prediction model was estimated from available data:

average foot volume	0.0014 m^3;
area of uppers	0.040 m^2;
area of sole	0.021 m^2;
rectal temperature	37 °C;

mean body skin temperature	33 °C (at T_a=-10.7 °C),
	33 °C (at T_a=+2.8 °C),
	32.5 °C (at T_a=-11.8 °C),
	32 °C (at T_a=-24.6 °C).

The other input data was left the same as default (Lotens, 1989).

The average dorsal foot skin temperature of all subjects was used in the analysis. The regression analysis and paired t-tests were used to acquire correlation coefficients and for statistics.

4. Results and discussions

The results that are not included in the publications are shown and discussed here, together with the summaries of the results and discussions of the published papers. The full results and discussions of the published studies are given in respective papers (Paper I-X).

4.1 Thermal effects of steel toe caps in footgear (Paper I)

The difference between double determinations of insulation with the thermal foot model was usually less than 0.005 m^2°C/W (about 2 %). This indicates high accuracy and reliability of the method. The observed differences between the boots with and without steel toe caps as well as the changes in heat loss can thus be considered valid. The experimental results showed no major differences between boots with and without steel toe caps.

There were no differences between insulation levels of boots with and without steel cap for one boot model (VN versus VS), but the differences were statistically significant for the second model (WN versus WS) showing slightly higher insulation values for the boot without steel cap. No significant differences due to insulation dissimilarities could be found from the measurements on subjects.

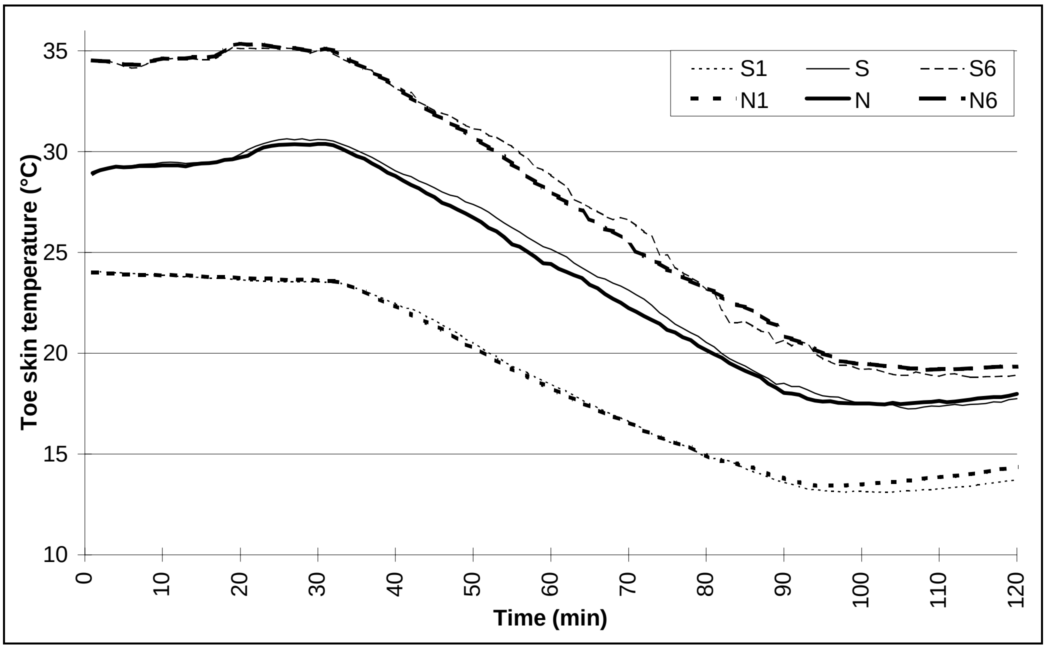

Figure 5. Mean toe skin temperature and the data of the subjects with the lowest and the highest toe skin temperature (S - steel toe, N - without steel toe; 1 and 6 mark subjects). On 30th minute the subjects entered the climatic chamber and on 90th they came out.

Statistically significant differences were found for both models regarding the rate of change of heat loss from the thermal foot model when its location was changed from warm to cold and back to warm. The rise and decrease of heat loss from the thermal foot model depended on the rate of temperature change of the boots. The results showed that a faster change in heat loss from the thermal foot model occurred for boots without steel toe caps. Data from subjects seemed to confirm this by a somewhat faster, though insignificant, rise in toe skin temperatures after cold exposure in boots without steel toe caps (Figure 5). The effect may be attributed to the higher mass and heat contents of the boots with steel toe cap.

The results showed that foot skin temperatures under cold condition tended to stay somewhat higher in boots with steel cap. However, when the subjects came out to a warm room, the foot skin temperatures in steel capped boots dropped more compared to boots without steel cap. This effect can be especially seen on the toe skin temperatures. A similar tendency was present for toe skin temperatures of all subjects. The re-warming of the feet after cold exposure takes longer time in boots with steel toe caps.

The small differences in the subjects' foot temperatures, although not significant, may reflect the difference in heat content. Although, boots without steel cap had higher insulation, the foot temperatures in these boots stayed lower in cold conditions than those in boots with steel toe cap. At the start of the trials, the subjects were seated at room temperature for 30 minutes with the boots on. During this time the feet temperatures rose and the boots could thus gain heat. In the cold, the feet stayed warm longer in with steel cap due to the higher heat content of these boots. Especially noticeable was the effect on the toes where the extra mass was located. After coming out from the cold, the situation changed - the extra mass kept the feet cold longer.

4.2 Effect of footwear insulation on thermal responses in the cold (Paper II)

4.2.1 Skin temperature

At environmental temperature of +3 °C there was no significant differences in 5-minute mean values between BS and AS at any measured place or for average skin temperatures. Differences in temperature changes were also insignificant.

At -12 °C the significant differences in 5-minute skin temperature means were present in all measured places and for average skin temperatures between BS and all other used boots. BS was significantly colder than the other boots. The biggest differences were in heel and the smallest in toes. The highest difference in insulation levels was in the heel where BS has the lowest value, while toe insulation is quite high in BS, AN and AS, and relatively low in WN and WS. In studies with a thermal foot model in wet conditions (Endrusick et al., 1992; Paper III) was shown that when the footwear got wet, the insulation level was strongly reduced. In the latter study the insulation of toes of WN and WS became closer to the levels of boots without an insulation layer.

There were no significant differences in skin temperatures between the other boots at the environmental temperature of -12 °C. However, significant differences in temperature changes were present between all the boots at certain time intervals, i.e. entering the chamber, changing activity and coming out from the chamber. A general tendency was that the boots with lower insulation cool quicker and warm quicker as well. Again the differences were bigger in heels than in toes and feet. The differences were generally insignificant between AS versus AN, and WS versus WN. The highest differences were between BS versus WS and WN. From the beginning of walking the foot skin temperature increased due to the increased heat production. The rise was quicker in boots WS and WN due to their better insulation. In other boots the foot skin temperature rise was slower and somewhat delayed. In toes such a change was minimal and generally their temperature kept dropping. Apparently, the exercise duration was too short. The toes would warm up only after 15-20 minutes of exercise (Rissanen & Rintamäki, 1998).

At -25 °C significant differences in skin temperatures between boots AS versus WS and WN occurred. Temperatures were higher in boots with higher insulation. In toe skin temperature the differences were insignificant. In temperature change the significant differences were present at activity and environment change and more so in heels. The changes were quicker for AS.

The most significant differences between the boots were found in heels probably due to the fact that the insulation differences between the boots in that zone were the biggest. Although the heel zone insulation was the lowest for boots AS, AN and BS, the heel temperature was kept higher than toe temperature. Only at the start of the exposure the heel temperature could be lower than toe temperature. Also, the warming effect of activity was highest in the heels. It could be related to that the heel is more central to circulation than the toes and not so physically protruding as toes. The pumping of warm air from calf region was to affect heels easier than toes that are relatively distant.

The skin temperatures in the same boots at different environmental temperature differed significantly. However, the differences started at different time points. It can be easily understood that the feet in the boots with higher insulation are less affected by environmental temperature than in boots with lower insulation.

It seems that the differences in the insulation of footwear begin to influence feet temperatures only from certain environmental temperature. During longer exposures at the same low activity level probably the differences should appear little by little as the feet temperatures keep dropping in all types of boots. Similarly, at a higher activity level the differences should appear quicker because of that insulated boots preserve the heat better. Thus, the combination of ambient temperature, activity and footwear insulation is critical for foot skin temperature. Considering the fact that in wet boots the toe insulation of WS and WN is lowered and did not considerably differ from the other boots (Paper III), then the toe skin temperature should drop similarly and be the limiting factor for exposure time.

The differences could also be related to boot material. The evaporation resistance seems to have great influence. BS had only a slightly lower insulation, but the higher evaporative resistance increased moisture concentration (Paper III) making it significantly colder at low environmental temperatures. Without the possibility to transport moisture further from the feet or absorb it in boot material, the nearest layers to the foot (skin surface and socks) become wet, and promote heat losses.

4.2.2 Subjective responses

Linear regression fitted thermal sensation quite well. However, for pain sensation a polynomial regression fitted better. When thermal sensation correlated best with mean foot skin temperature, then pain sensation had best correlation with toe temperatures (R=0.658, polynomial). Generally, the subjective responses followed the skin temperatures. The change in pain sensation did not have linear relationship with skin temperature.

Statistical analysis of thermal and pain sensation showed few significant differences between boots at various temperatures. At -25 °C AS was perceived significantly colder than WN. At -12 °C BS (rubber boot) was perceived to be significantly colder than WS/WN. Generally, WN and WS were perceived to be the warmest and BS the coldest in accordance with the measured insulation values. In pain sensation the significant differences at -12 °C were present at the end of cold exposures and start of warm breaks between BS and other boots. Pain in feet was greater in BS than in other types of boots.

Thermal regression agrees with previous observations (Enander et al., 1979; Luczak, 1991) that the feet generally start feeling cold at around 25 °C and when the feet skin temperatures drop under 20 °C then a strong perception of cold occurs. Still, the distribution was very wide. While the responses of some subjects at mean foot skin temperature of 20-25 °C were still neutral (0) or even slightly warm (1), then the responses of the other subjects indicated already very cold feet (-4). Even the same subject in similar condition, e.g. WS and WN at -25 °C, could show considerable differences in the thermal sensation, indicating variation in whole-body heat balance rather than feet temperature. Slight pain could occur when feet temperatures were around 20-23 °C and at temperatures under 20 °C pain quickly grew. However, when feet warmed up again then a pain sensation could be present due to vasodilatation and increased blood flow to feet (strong and quick warm sensation).

The correlation was strongest between subjective responses and mean foot skin temperature. However, the cold or pain sensation was often connected with a particular foot part: heel for some subjects, but toes for most of them. This agrees with the conclusions of an earlier study (Rintamäki & Hassi, 1989a) on subjective response dependence on lowest temperature in the feet. The toe skin temperature was considerably lower than mean foot skin temperature when subjects gave their cold and pain response. Toes started to feel cold at around 20-22 °C and strong perception of cold occurred around 15 °C. Pain occurred around 15 °C and grew quickly with a decrease in toe temperature. Drop of toe skin temperature below 12 °C was connected with very strong pain.

For boots with lower insulation (AS and AN) toe skin temperature was generally lower in boots without steel toe. At the same time for boots with higher insulation (WS and WN) there was opposite tendency. It could be possible that at low insulation level steel toe has more important role as additional insulation layer, while this effect becomes negligible at higher insulation levels and some other factors have greater influence, e.g. mass (heat content). Regarding thermal sensations, there was a similar tendency. AN showed just somewhat quicker warm-ups than AS. At the end of the second cold exposure and beginning of warm-up pain sensation in AS was greater than in AN. At -12 °C there could hardly be seen any differences in pain and thermal responses for boots WS and WN, while at -25 °C feet in WN seemed to have somewhat lower cold sensation and less pain. However, these differences were insignificant both statistically as well as for practical use.

For safety shoes in cold climate the fit is ranked first by users and manufacturers and second by experts, while thermal comfort is ranked first by experts and second by users and manufacturers (Bergquist & Abeysekera, 1994). After each trial the subjects were asked about the general comfort of the boots. Boot WN got the highest rating and AS the lowest one. It can be assumed that thermal comfort has an influence on the subjective ratings of general comfort of the footwear, still, the comfort rating for coldest boot (BS) was higher than that for AS and AN. The low values for AS could be connected to poor fit of the boot. The heel of some subjects moved up and down in the boot, while other subjects complained about pain from pressure onto lateral heel (between heel and ankle bone).

4.3 Effect of sweating on insulation of footwear (Paper III)

The mean difference and standard deviation for the double determinations for the insulation of 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, respectively 0.006±0.006 m^2°C/W and 0.004±0.003 m^2°C/W in wet conditions. Difference between replicates in dry conditions was less than 2 % of the mean value for all measurements, respectively 3 % for wet conditions. Differences between means of double determinations for different shoes exceeding 4 %, respective 6 % would then be significant ($p<0.05$). The values for dry conditions agree with previous results from an earlier study (Bergquist & Holmér, 1997).

Only a small amount of water was evaporating through the boots. The boots with insulation layer had less water in socks than the boots without it. 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.

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 have any significant differences.

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

- the evaporative heat loss in addition to dry heat loss;
- the drop in effective insulation due to wetted layers.

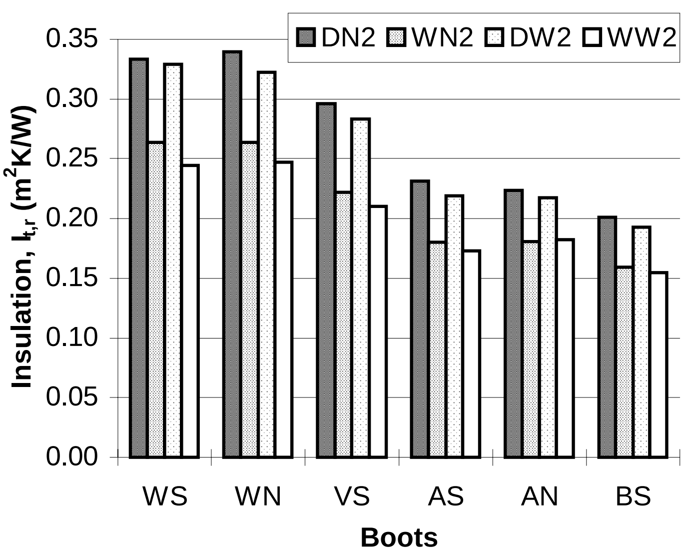

Figure 6. Effect of wetting and weight. Zones from toes up to and including ankle. All tests are with sock 2. DN2 - dry without weight; WN2 - wet without weight; DW2 - dry with weight; WW2 - wet with weight.

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

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. 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 study shows that weight influence depends also on sole material.

The study by (Endrusick et al., 1992) showed considerable reduction of thermal resistance of the footwear that were immersed for 18 hours into 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) similar reduction occurred already after 1.5 hours.

The slight differences in evaporation and water gain in socks can be explained. Boots with insulation (W and V) had lower amount of water in socks because the insulation could absorb water better and the evaporation was more difficult. During walking the effect of evaporation could be bigger than measured in static conditions.

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. For the boots without special insulation layer (A and B) the coldest zone seemed to be the heel. Generally, the insulation of these boots in all zones was homogenous. For the boots with 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 wrist. 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.

4.4 Change of footwear insulation at various sweating rates (Paper IV)

4.4.1 Tests at various flow rates

Figure 7 shows the total insulation reduction of boots at various sweat rates. Even a sweat rate of 3 g/h reduced the insulation considerably. The insulation reduction was related to dry insulation values. The total insulation reduction for footwear was 9-14 %, at 3 g/h, for the warmest footwear (SM) 19 %. The same values at 5 g/h were 13-20 % and 27 %, and at 10 g/h, 19-26 % and 36 %, respectively.

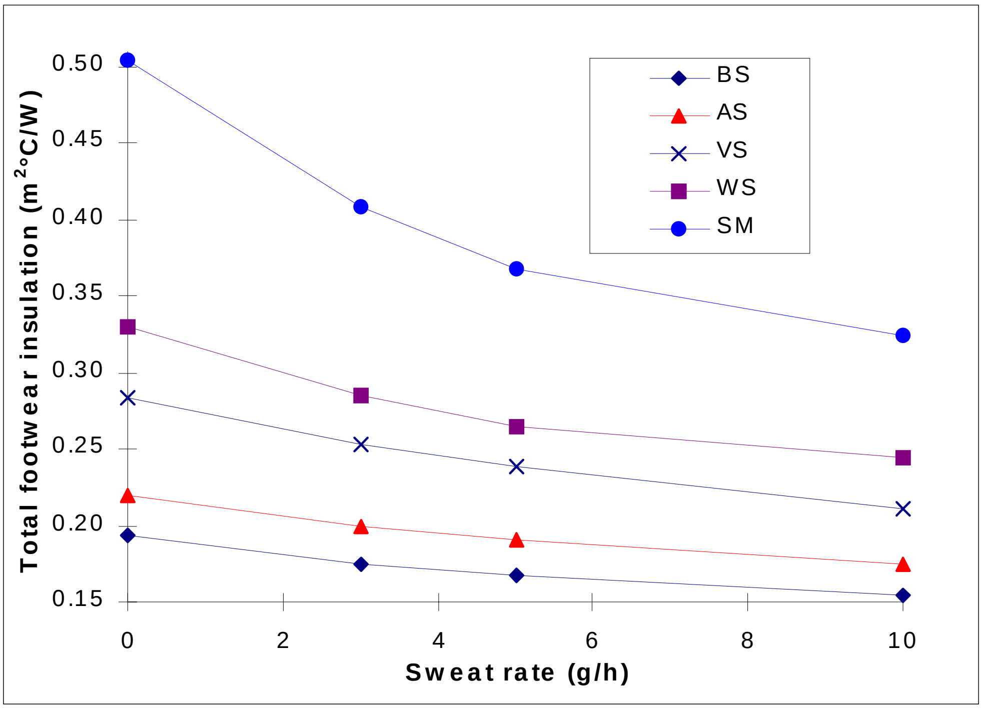

Figure 7. The change in total footwear insulation due to sweating.

In the toe zone the insulation reduction was even higher and reached 47 % at 10 g/h for SM while for others it was between 28 and 40 %. Such a big reduction could be partly related to one "sweat gland" being located on the top of the toes. At 3 g/h the reduction of toe insulation was 19-22 % for most of footwear and 28 % for SM, and at 5 g/h it was 24-27 % and 36 %, respectively. The lower reduction for total and toe insulation corresponded to lower initial footwear insulation. It is unknown whether the reduction of the toe insulation would be so big in real wear conditions. However, some studies (Gran, 1957; Keech et al., 1970) have shown that the toe, sole and heel part of shoe and hose take up more moisture than other parts.

It is known, that the humidity moves towards the cooler areas because of the water-vapour pressure differences. This process could be quicker during walking that is accompanied by the pumping effect. Rewarming of the feet during exercise was related to the pumping created air motion inside the footwear (Rissanen & Rintamäki, 1998). Simultaneously, the moisture should be carried with air, as well. As the toes are usually the coldest region, the humidity would condense easily in that location.

Based on the results of this study, 2 equations were developed to predict the insulation reduction of the footwear. These equations show the reduction after 1.5 hours at a certain sweat rate. Equation 4 is for the whole foot and Equation 5 for toe zone only:

$$I_{wet}=0.00087+0.012 \cdot SW-0.00064 \cdot SW^2+I_{dry} \cdot (1-0.093 \cdot SW+0.0047 \cdot SW^2) \quad (4)$$
$$I_{wet}=0.0011+0.014 \cdot SW-0.00078 \cdot SW^2+I_{dry} \cdot (0.99-0.13 \cdot SW+0.0071 \cdot SW^2) \quad (5)$$

I_{wet} is insulation after 1.5 hours (m^2°C/W), I_{dry} is the dry insulation (m^2°C/W) and SW is the sweat rate (g/h). The correlation coefficient between measured and calculated values was 99 % for both cases. The mean difference between measured and calculated values for the total insulation was 0±3 % (from -9 to +7 %) and for toe insulation -1±4 % (from -9 to +10 %).

The equations are valid for standing still. Walking generates heat and the feet would stay warmer. Only when stopping and standing still, would the cooling effect of reduced insulation be fully noticeable. Some studies with walking, or walking and sweating, could be used as guidelines for insulation reduction for those conditions (Bergquist & Holmér, 1997; Paper V).

During the tests the evaporation was small, in average about 10 %. Generally, the evaporation rate was related to sweating rate. At sweat rate of 3 g/h it was 0.3 g within 1.5 hours, at 5 g/h it was 0.5 g and at 10 g/h it was 1 g. Based on average evaporation over all sweat rates, the highest evaporation was in SM with 1.4 g, followed by AS 1.2 g, BS 0.6 g, VS 0.4 g and WS 0.2 g within 90 minutes. On average 64 % of the moisture stayed in the boot and 29 % in the sock. For WS and VS these values were around 70 % and 26 %. SM was different from the others with in average of 48 % staying in the footwear and 35 % in the sock. The evaporation percentage was more than twice as high as in the other boots (17 %).

SM dried out quicker than the other boots. This could be related partly to the fact that the insulation layers (double felt inner-socks) could be taken out. In this boot the largest amount of moisture stayed in the middle-layer 27 %, 13 % stayed in the shell and 8 % in inner-boot. As sweat rate increased the moisture percentage in the inner-boot increased, and reduced in the middle-layer and shell. This could be related to the capacity of the moisture transport of the inner-boot.

4.4.2 8-hour tests

The use of five “sweat glands” with equal flow gave similar total insulation reductions as for 3 “sweat glands”. However, the local insulation reduction could differ. Toe zone insulation reduced on average 4-5 % less during the first 1.5 hours, while the reduction increased in mid-foot, ankle and heel zones. This is consistent with the redistribution of the water amount from the toes to these zones.

It appeared that the insulation change within the first 1.5 hours corresponded to most of the total reduction during the 8-hour sweating in warm winter boots (Figure 8). The next 6.5 hours reduced the insulation only 4-5 % more in WS and 8-9 % in SM. For a leather boot (AS) the reduction within these 6.5 hours was around 10 %, a value that corresponds to somewhat less than half of the total reduction for 8 hours. By the end of the 6 hours of wet measurements the insulation had reduced as much as during the first 1.5 hours for the rubber boot BS.

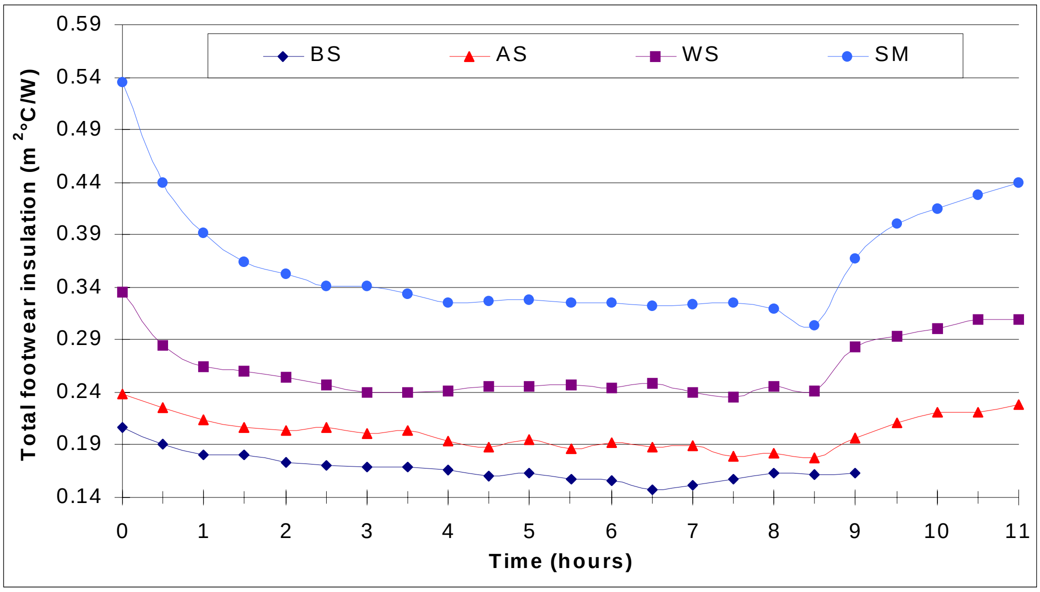

Figure 8. The change in footwear insulation due to sweating over 8-hour period (6 hours for BS) and during 3-hour follow-up without sweating.

BS was also the footwear that did recover least within the last 3 hours of the dry test. In comparison to the dry insulation value it regained only 4 % of the insulation it lost during the 6 hours of wet testing. At the same time, AS and WS regained about 19 % of the insulation they lost during the 8 hours of wet test. For SM this number was 22 %.

The evaporation from the footwear was highest in AS and SM, 1.8 and 1.4 g/h over the period of 11 hours. 0.8 g/h evaporated from BS (9 hours) and from WS 0.4 g/h (11 hours). Moisture distribution in the footwear and socks was different after 8 and 11 hours. In the very end, relatively more moisture was concentrated in outer layer (boot). This can be best described in SM, which had three layers that could be weighed separately (Table 7). In the winter boots and AS the socks had become almost dry by this time (3-5 g water at 8 hours and 0-2 g in the end). That was not the case for the rubber boot. Although, the sock had less water in, it was still quite wet (8.9 g at 6 hours and 4.5 g in the end).

Table 7. Water distribution in different layers of boot SM at the end of wet test (8th hour) and after 3 hours without water supply (11th hour).

Layers	Dry weight (g)	Water distribution at 8th hour (g)	Water distribution at 11th hour (g)
Sock	19.5	4.0	0.0
Inner layer	110.7	4.4	0.5
Middle layer	190.0	18.8	16.6
Outer shell	929.3	6.8	8.0

The insulation reduction levelled off in the long test. This indicates that a balance was reached between the water supply and the evaporation and water transport. In the rubber boot BS this balance was not reached. BS had not much capacity to absorb and transport the water further from the foot. The sock became more wet and favoured further cooling, even when sweating was stopped the insulation did not improve much. From this point of view the leather boot functioned much better. This agrees with the results of testing the materials with various permeability and the discussion on the effects of moisture absorption and transport of the materials on human comfort sensation (Kim, 1999).

The winter footwear and the leather boot gained back a considerable amount of insulation within the 3 hours of dry measurements. The water was absorbed and transported further away from the foot. The sock became relatively dry. This demonstrates the importance of keeping the layers near body dry. Although, the amount of water in the boot was still relatively high, for example, 36.6 g in WS, the total insulation at 11th hour was only 7.5 % lower than dry insulation. This suggests that changing socks after heavy activity can be an effective way to keep feet warm over the day.

The morning after the long test, the footwear was weighed again. The most moisture was left in WS - 24 g. The remaining moisture in AS, BS and SM was 11 g, 2 g and under 2 g respectively. The good drying of BS may be related to the fact that the boot did not consist of materials that could absorb much water. SM probably dried as well as it did because the insulation layers could be taken out. A lot of the moisture in WS seemed to stay in the toe zone; during the manual examination this area felt wet.

Analysis of the results from the long test and the tests at various sweat rates, indicates that equations 4 and 5 can be used for the estimation of the insulation decrease even for longer periods. However, when total insulation change was similar (equation 4) even with the redistribution of the water with more “sweat glands”, then this redistribution affected the toe zone (equation 5). The insulation decrease in the toes was about 5 % less with more even water distribution. Simultaneously, separate predictions according to the equations could differ up to ±10 % from the measured values (SD ±4 % for toes). For the boots with insulation layers the total insulation drop within the next 6.5 hours should be under ¼ of the change within first 1.5 hours, while for thin boots the further drop could be as much as for the first 1.5 hours. The equations were not checked for the situation where the footwear is not dry in the beginning of the day.

4.4.3 Tests in warm chamber at +34 °C

This condition allows the evaporative heat loss to be studied separately. All the heat loss was considered to be evaporative and was taken equal to the supplied power. The comparison was done on the basis of the power to the foot model. The biggest evaporative heat losses were from ankle and mid-foot zones, the lowest from toes and sole. This could be easily understood as ankle and mid-foot are closer to the collar opening. However, one should be aware that in cold ambient conditions the evaporation could have been higher than in warm conditions. In the cold the temperature gradient between foot model’s surface and footwear material was larger, and thus the vapour pressure difference and condensation rate could be higher. The temperature gradient has shown to have an effect on moisture vapour transport on waterproof breathable materials (Gretton et al., 1998).

In addition to the evaporative heat losses measured with the foot model, these heat losses were also calculated from evaporated water. For footwear AS and SM the calculated values were only slightly lower than the measured ones. Footwear BS and WS had big differences. This could have to do with vapour permeability. AS and SM had relatively high evaporation in each of the wet conditions, while BS and WS had low evaporation rates. The high measured, compared to low calculated, heat losses from BS and WS could be related to the evaporative heat transport from the foot surface to the boot inner surface. During condensation the heat was released. Part of the heat was given to the environment and part of it stayed in the footwear, while most of the water stayed in the footwear.

A similar result was reported with testing of clothing on a thermal manikin (Kuklane et al., 1997b). The thermal manikin in that study emitted all water as a vapour. It was considered that 60 % of the condensation heat transferred to the environment and 40 % reduced the need for heating power. In the present model the water was transported further from model's surface both in liquid and in vapour state. This makes it difficult to determine how much of the total water evaporated and condensed, and how much was transported in liquid form.

During the comparison with the warm-wet test, it seems clearly that the evaporative heat losses counted for the higher part of the reduction in total insulation, with the exception of the rubber boot BS. In winter footwear a considerable part of the total insulation reduction was also due to the other reasons, e.g. higher heat conductivity of water between insulation fibres. However, in the toe zone the situation was quite different. Evaporation was relatively low and other factors had relatively high importance on the insulation reduction with the exception of SM where both factors had equal importance. This could result from the more restricted evaporation from toes.

4.5 Reduction of footwear insulation due to walking and sweating (Paper V)

Figure 9 shows the total insulation of the boots in all 4 conditions. The insulation of the whole boot reduced due to walking less than 10 % for warm winter boots and 32 % for rubber boot. This agrees with a previous study (Bergquist & Holmér, 1997). That study noted also the biggest reduction in a rubber boot and relates it to the flexibility of the material that could enhance possible pumping effect. The reduction of the total insulation due to wetting and walking was 37- 46 %. The reduction of the insulation due to sweating during standing has been discussed in other studies (Papers III and IV).

The insulation of the toes reduced up to 55 % due to sweating and walking compared to the standing and dry. Here should be remembered that one "sweat gland" was located on top of the toes. Walking in dry condition reduced insulation of toes up to 10 % in warm boots and 26 % in rubber boot. These values are also in the range of those that were reported in an earlier study (Bergquist & Holmér, 1997).

The sole insulation changed differently. During walking condition the insulation of boot WS even gained compared to dry standing condition. For boot VS the picture was similar, although less pronounced. Even for BN this effect was noticeable. The effect could depend on following reasons:

- less heat loss from conduction
- heat production from friction between the foot model and the sole
- heat production from friction between the sole and the walking surface

Unluckily the changes of sole insulation differences between static and dynamic conditions were not reported by Bergquist & Holmér (Bergquist & Holmér, 1997).

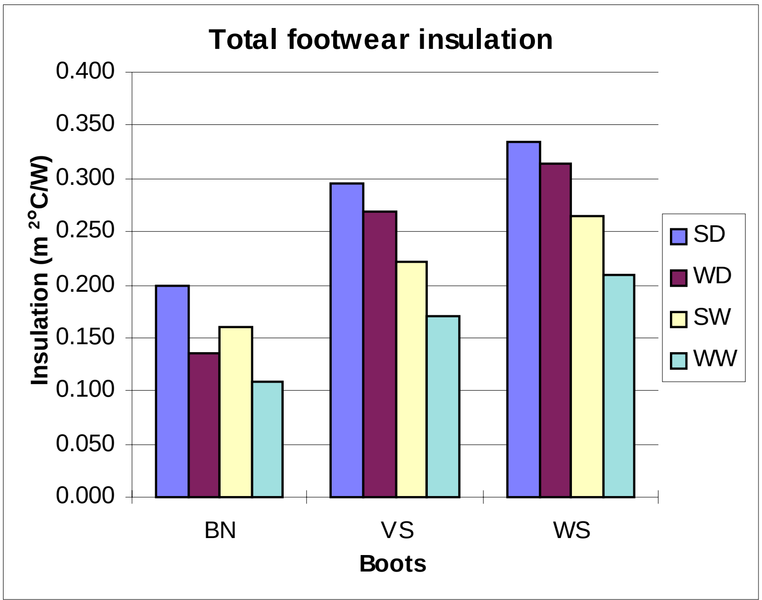

Figure 9. Total insulation of footwear. Toe, sole, heel, mid-foot and ankle zones are included. Conditions: SD - standing dry; WD - walking dry; SW - standing wet; WW - walking wet.

4.6 One week sweating simulation test with a thermal foot model (Paper VI)

The insulation change over one week (dry value in the morning of the first day and values for the end of each day) is shown in Figure 10. Moisture collection in footwear is shown in Figure 11. The sock dried to start weight over night at room temperature and in the refrigerator (boots WS, WN and SG). In boot SM, that was conditioned in a box with high humidity, the water from sock did not evaporate totally over night. Each next morning it was about 1-3 g heavier than in the beginning. The moisture collection in the sock increased with days. SM, when conditioned at low humidity (in refrigerator, SM2), dried practically to dry weight over the night and insulation reduction over each day was similar. There was no difference in insulation change between the days.

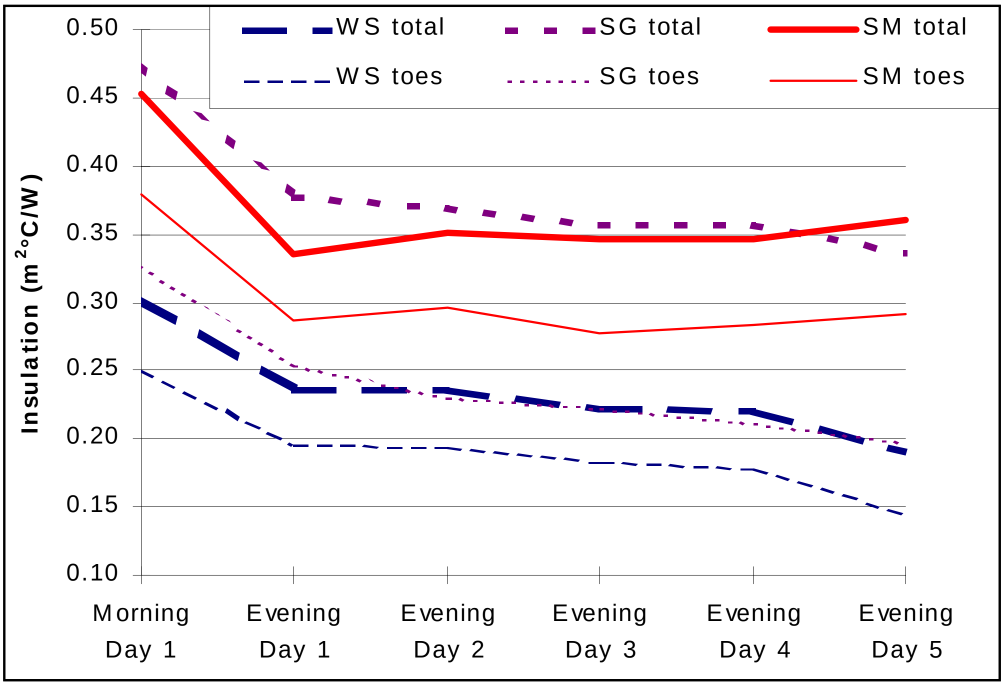

Figure 10. Insulation change. Condition description: Morning Day 1 - first hour of the first measuring day without sweating (dry insulation), wind 1.5±0.5 m/s, up-down motion (8 steps/minute); Evening Day 1 to 5 - last measurement of the day, sweating 5 g/h, wind 1.5±0.5 m/s, up-down motion (8 steps/minute). WN changed similar to WS.

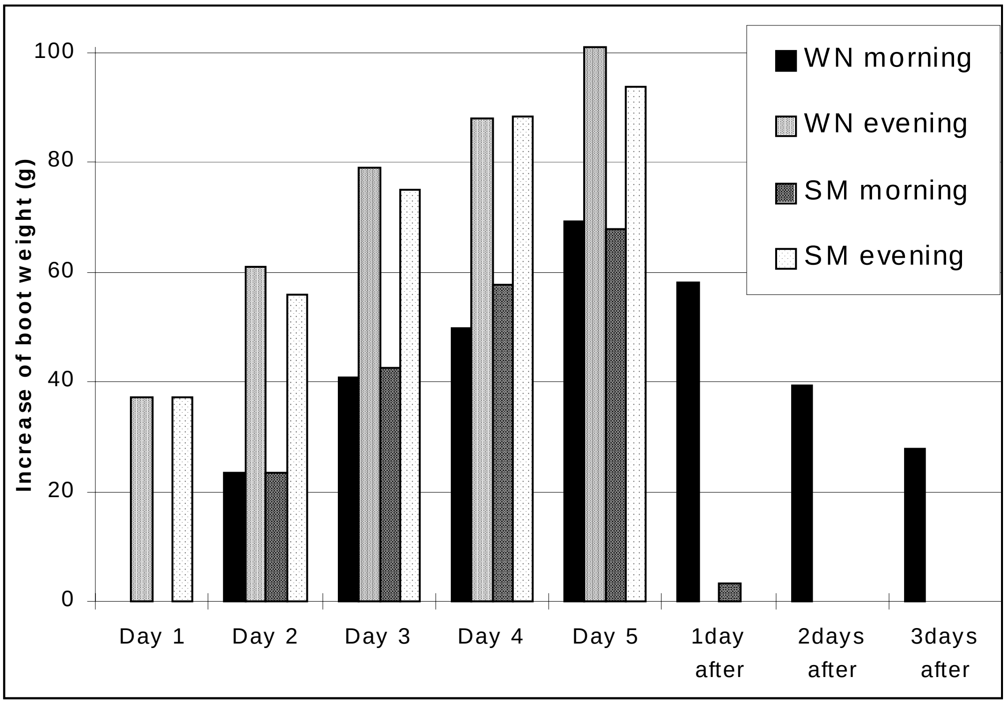

Figure 11. Weight gain in footwear WN and SM over the week.

In the end of the second day there was observed little frost between shell and inner-boot of SG and between outer and middle layer of SM. The amount of frost increased with each following day. In the end of the last day there was considerable amount of frost between middle layer and insole, between middle and outer layer and some frost between inner-boot and middle layer of SM. Middle and outer layer had frozen slightly together. After 5 days testing the boot was left at the room temperature and it dried almost to the initial weight within one night (Figure 11). SG dried better in the refrigerator and the amount of frost between layers did not increase as much. However, drying at room temperature to initial weight took longer time for SG than for SM. In a second series with SM at low humidity level (SM2) the layers except middle layer dried totally out. Even in the middle layer the weight gain was under 10 g over the 5 day period.

The footwear insulation reduced considerably over 5 days period (Figure 10). The biggest reduction occurred during the first hours of the first day, and could be related to the onset of sweating. Similar, but somewhat smaller change was observed in the beginning of each day. General trend was towards lower insulation both in the morning (reduction due to gained moisture left in footwear) and in the evening (reduction due to gained moisture and evaporation in footwear).

No specific differences could be observed between footwear with (WS) and without steel toe cap (WN) due to the moisture accumulation in footwear. The explanation to the complaints on the cooling effect of the steel toe cap could be just related to the after-effect (Paper I), that could depend on higher mass, and thus slower warm up of the steel toe capped feet.

Within a 5-days military exercise it has been shown that footwear can gain totally more than 400 g (per pair) already within first 2 days of exercise even in relatively good weather conditions (Martini, 1995). In the present study the boots gained about 100 g of moisture per boot by the end of the last day. The water did not totally evaporate from the boots WS and WN even at room temperature over night (Figure 11). These footwear dried relatively well around ankle, but the toe area felt soaked during manual examination in the beginning of the tests on last days. This explains also the low insulation values in the toes. The wet insulation layers probably made the sock wet enhancing the heat loss from the toes already in the beginning of the test.

During the tests there was practically no evaporation from the footwear due to low environmental temperature. Some evaporative heat exchange could be present inside the footwear, i.e. evaporation from the foot surface and condensation in boot layers. As the humidity concentration in footwear was high, the evaporative heat exchange could be driven mostly by temperature gradient. The main heat losses could be related to the increased heat conductivity of the wet footwear insulation.

4.7 Questionnaire survey

4.7.1 Work organisation and background data

In total 43 questionnaires out of 66 were returned: 18 from harbour, 16 from telecommunication, 8 from customs and 1 from a construction worker working at the institute by contract. Only 2 respondents were women and they both worked at the customs. The persons represented a wide variety of jobs that have to be carried out in cold working conditions. The age of the workers was between 21 and 60 years. In average they had worked in their respective company for 18.5±10.4 years.

According to the respondents an ordinary workday consisted of 18.7 % very light, 23.2 % light, 21.5 % moderate, 29.3 % heavy and 7.3 % very heavy work. 57 % of the work time was spent in cold environment. The total amount of cold exposure during a full working day depended on the environmental temperature and was at average more than 4 hours at 0 °C, about 4 hours at -10 °C and 2-4 hours at -20 °C. The length of cold exposure was dictated by the job needs. Temperature of -20 °C was considered enough severe to limit the exposure time. The length of one work period in cold was usually 1-2 hours. At -20 °C it was under 1 hour, except for the customs where work periods were always around 1-2 hours. Usually, it was possible to take a warm break when a person felt cold. However, there could be as well occasions where there was not possibility to take a break because of feeling cold. Sometimes the workers themselves did not choose to take a break for warming up even when there was a possibility. Generally, there were breaks in warm locations about 3 times per day. The length of an average break was around 30 minutes. If there were more breaks, then these were usually shorter. Usually, there were seldom (1-2 times) tasks at warm locations. Only at the customs some tasks were carried out in warm locations up to about 5 times per day. These work periods in warm places usually lasted about 15-60 minutes.

The most workers (72 %) considered the wintertime to be the most troublesome season regarding the footwear. Cold was the main reason for that. The other reasons were wetness, snow and ice, bulkiness (weight) of the winter boots that makes it difficult to carry out some tasks (reduced mobility), darkness. Two workers (<5 %) considered the spring-fall periods as the worst. One of them considered in his answer the difficulty to choose the right footwear for work due to the quick weather changes. Nine workers did not answer the question and 1 had not had any trouble with the footwear.

4.7.2 Used footwear

Only one of 43 workers said that he did not use the safety shoes (footwear with steel toe cap). However, 8 (3 from telecommunication and 5 from customs) said that the safety shoe was not compulsory (including one who didn't wear them) and one did not answer on the question. Generally the same pair of the footwear was worn longer than 6 months (44 % 6-12 months, 28 % 1-2 years and 26 % more than 2 years). 67 % used the same safety footwear every day and 30 % used the same footwear both during summer and winter. At customs all wore the same footwear every day (harbour 2/3 and telecommunication more than half) and only one used different boots during summer and winter, while at telecommunication there were only two persons who reported to use the same footwear during summer and winter (harbour 5).

At harbour most of the workers (12) used footwear with warm lining during winter. Half of them used also footwear without lining occasionally (5) or constantly (4). Telecommunication workers used warm boots and one of them used footwear without lining occasionally while at customs all the workers constantly wore footwear without lining. They had high leather boots with a zipper and/or cords. At other companies the leather was the most common footwear material, too. However, some footwear of synthetic material (3 at both) or rubber boots (2 at harbour and 1 at telecommunication) were used as well. At telecommunication the used footwear was usually of boots, while at harbour on 50 % of cases the shoes were used. The most common high footwear was with the zipper, while low shoes commonly had cords.

4.7.3 General problems with cold

Most of the persons reported trouble with cold. Often the cold became most unpleasant when it was connected with wind (23 % always, 40 % at least once per week and 23 % 1-2 times per month). The most common cold body parts were feet and toes (84 %) followed by hands and fingers (79 %) and face with its components (ears, chin, cheek etc., 79 %). The cold sensation was the severest in hands and fingers, followed by feet and toes and then face and its parts. The legs were the next to feel cold. The three most highly ranked factors for cold sensation of feet were boot material (42 % of respondents), contact with cold surfaces (37 %) and work at varying activity levels (14 %). In addition, the jobs that require long periods of standing still were mentioned as a factor for cold feet.

Some workers (14 %) had a cold injury at work and some (14 %) during free time. One person reported a cold injury both at work and free time at the same location. Some had cold injury at two or more locations. The listed sites were toes (5 cases), fingers (3), ears (3), nose (1), under chin (1), eyelid (1), cheek (1) and an unspecified location on face (1). Some workers had stumbled because their feet were cold (16 %).

50 % of workers were satisfied with their clothing. However, this picture was different in various companies. At harbour 40 % answered that their clothing does not protect enough well against cold. At telecommunication the percentage of dissatisfied was 30, while none from customs was satisfied with cold protection of their clothing. The footwear was considered to be the worst (30 %) followed by outer garments and gloves (both 23 %). At different companies the dissatisfaction was different: at harbour (18 workers) the three biggest problems were footwear (33 %), gloves (28 %) and outer garments (22 %). At telecommunication (16) there was most few complains on clothing: footwear 19 %, gloves 13 % and on socks, cap and gloves all 6 %. The most dissatisfied were customs workers (8): 75 % complained on outer garments and 50 % on footwear and gloves. At all companies 44 % used the thick warm socks. Extra insoles were used by 19 %. Some of the complaints were related to cold steel toe cap in footwear and “footwear too small to allow additional insoles or socks”.

4.7.4 Slipping and other problems with footwear in cold

47 % of the workers (harbour 50 %, telecommunication 31 % and customs 75 %) had experienced problems with footwear in the cold climate. This was well related to the type of the used footwear. Twenty one workers gave their comments on what could be the problem. Nine of them (43 %) directly point out steel toe cap or other steel objects in footwear as a cause of cold feet. Other problems were

connected with cold soles (6), slippery soles (3), shoes were experienced colder than boots, but some jobs, e.g. driving a forklift truck were seen more comfortable with them, jobs that require long periods of standing still, fresh snow after heavy snowfall (more than 20-30 cm), missing a good support at ankle, too low, not insulated (especially customs) or just cold itself. Finally, there was a suggestion to use boots with cords that fit better around the ankle instead of ordinary leather boots.

The most problems connected with footwear were feeling cold in feet (30 of 43) followed by risk to slip (16) and wet (15) or sweaty (12) feet. The main reasons for cold feet was seen to be footwear without warm lining or bad insulation (3), steel toe cap in safety footwear (3), work that requires long periods of standing still (2) or low sole insulation (1) and severe cold in itself (1). The supposed reasons for slipping were wrong choice of the sole, incorrect soles and that the rubber becomes stiff with cold. Stiffness and missing good support at the ankle joint were the problems connected with boot material and construction (2). Two (2) workers mentioned slippery working/walking surfaces. Wet or sweaty feet were related to water from outside (snow, water and rain, 3) or inside (sweating, 1), shifting between cold and warm locations during day, no ventilation in footwear, wrong choice of footwear and no insulation (all 1). Bad fit (9) was related to not enough tight around shin, bad support for ankle, stiffness, wrong choice of shoes, can’t find the shoe fitting particularly one’s foot (all 1). Stiffness was brought out separately on 8 cases. Difficulties to walk (6) and restricted mobility (6) were related to stiffness (3), clumsy shoes, cold and slipperiness (all 1). Five (5) workers thought that their shoes affect the working and one (1) related it to the need to be more careful. Four (4) workers had had chafed feet. For one of them the reason was a hard heel-cup. One (1) mentioned the difficulty to put on/take off the shoes. Because of missing good support at the ankle and slipperiness the footwear was considered not to give enough protection against injuries (1). One (1) recommended laced boots against spraining and 1 mentioned the footwear tightness to be the reason for wet feet.

Slipping was considered as the next problem after cold. 30 (70 %) workers had slipped and 22 (51 %) had fallen during last two winter seasons. Only one of 43 workers had used some kind of anti-slip device and even that was used seldom and when it was a part of the safety footwear. Another worker mentioned that he used the boots with ribbed soles. Both of them thought that such footwear functions quite well. Of these 30 workers who had slipped, 6 had slipped often (at least once per week), 12 sometimes (1-3 times per month) and the rest seldom. Of the 22 workers who fell, had half fallen sometimes and half seldom. In five cases it had ended with an injury: ligament injury, caudal vertebra contusion, muscle strain and tooth injury, foot sprain and lumbago. The biggest slipping risks differed somewhat at various workplaces. At harbour the highest risk was connected with slippery deck (2), stepping on and off the machines (2), climbing up to crape off ice from machine windows, new machines, on top of the containers, under the crane and at small height differences (all 1). At telecommunication the highest risks were connected with icy masts (4) and climbing up the mast, walking at parking lots near stations or just on ground (all 1). At customs were the problems connected with climbing on and off the truck (4), oily terminals, slippery deck and brisk walk (all 1). The workers recommended to use salt (2), sand, chip the ice and shovel it away and better soles (all 1).

Some proposals as how to improve the situation were given: to use laced boots (similar to hiking boots) that are more tight around the ankle and shin area (2); there are available good boots on market, but the company (employer) provides just one type (2); buy boots with better quality (2); boots with warm lining needed (2); use another material for toe cap instead of steel; cover the seam at sole with sole material (rubber) to restrict water entering the footwear; use materials with high friction (tested for oily and icy surfaces) for soles; use materials of GoreTex type on sides to improve ventilation (all 1).

4.8 A field study at a harbour

As the weather was relatively mild throughout whole study period, the toe and foot temperatures stayed at considerably high levels in the insulated winter boots. Only a subject with his own shoes experienced cold feet.

4.8.1 Questionnaire at the end of the day

During the day the workloads varied and for each type of job the workload was somewhat different. In average the test persons rated their exertion very light 23%, light 20 %, moderate 47 % and heavy 10 % of total work time. In average they were working outdoors 4-6 hours and the length of an average work period outdoors was 1-2 hours. In average the test persons had 2-4 breaks during the day and the length of an average break was 30-45 minutes. The duration of warm work was less than 15 minutes per day. The workers were not disturbed by cold or were disturbed just occasionally. The workers related the cold sensation in feet to the footwear material (1 subject) and sweating (1) and considered these days similar or warmer compared to usual cold season workdays.

The footwear were considered comfortable except by 1 worker - he had chosen a too big size. The problems with the footwear were difficulty to walk, limited mobility and poor fit (1 subject), limiting effect on work ability (2), cold feet (a subject using his own shoes) and sweaty feet (1). A person, who often had to climb up and down platforms, considered the boots to be too heavy. Generally the boots were considered good and some workers were eager to get similar footwear. Two workers mentioned the boots to be “very good safety boots”. No subject had problem with slipping.

4.8.2 Foot skin temperatures

The foot skin temperature over time are shown in Figures 12 and 13. The foot skin temperatures stayed relatively high, usually over 30 °C. In subject 2 the foot skin temperature was somewhat lower already in the beginning. However, during the workday it raised higher than 30 °C. Enander et al (Enander et al., 1979) showed similar values for food processing workers in cold halls doing various

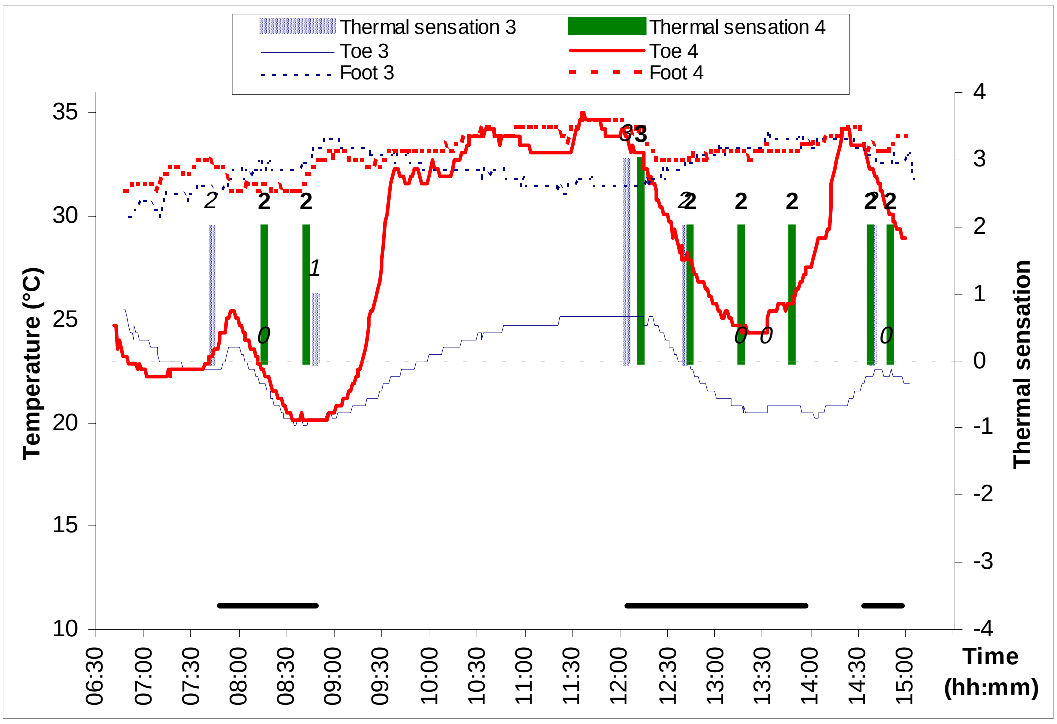

Figure 12. Foot and toe temperatures of subjects 3 and 4 (fastening steel). Thick lines at time axis show work periods in the cold. Columns and numbers show the thermal sensation in feet (*1* - subject 3; **1** - subject 4) at given time point.

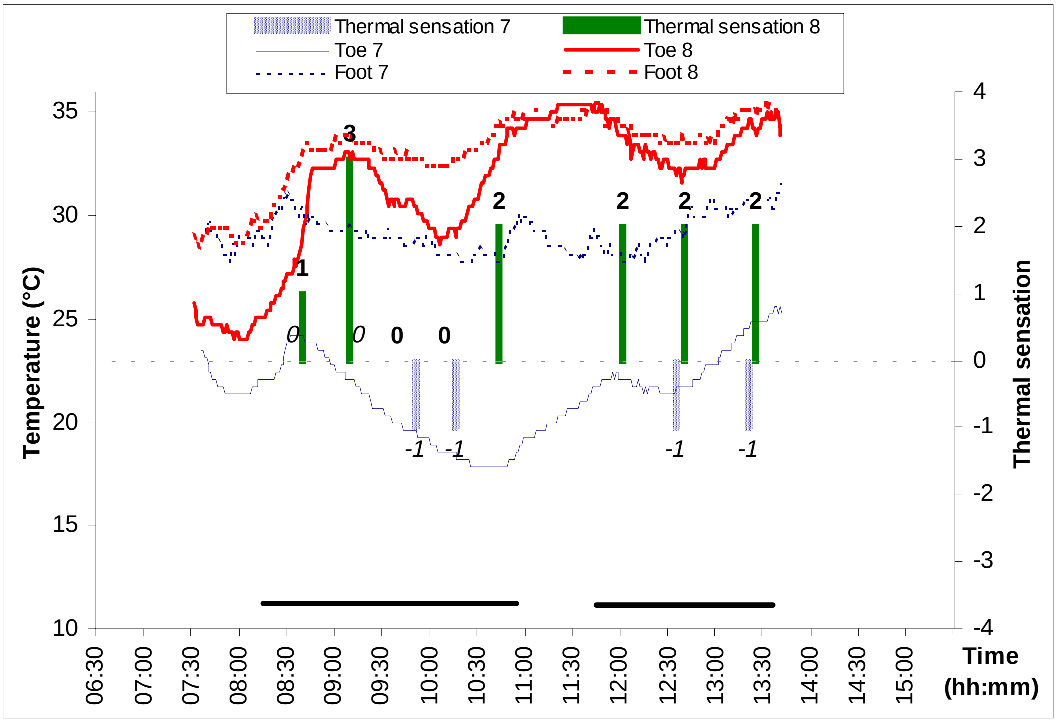

Figure 13. Foot and toe temperatures of subjects 7 and 8 (signalling). Thick lines at time axis show work periods in the cold. Columns and numbers show the thermal sensation in feet (*1* - subject 7; **1** - subject 8) at given time point.

jobs at 1 to 13 °C. The warm boots kept the foot skin temperature relatively constant for the whole workday. The thermal sensations of the feet (scale from +4 to -

4) were often warm or very warm. The exception was subject 7 who had his own shoes and during most of the day felt slightly cold in the feet. His foot skin temperatures stayed under 30 °C for most of the workday (Figure 13).

However, the toe temperatures varied more than the foot temperatures (Table 8). This could be related to the lower insulation of the toe zone (Paper III) and to the fact that the vasomotor activity is high in peripheral body parts. The lowest toe temperatures were occasionally between 17-18 °C. Commonly they stayed higher than 25 °C for most of the workday. In the beginning of the day most of the subjects had toe skin temperatures between 20-25 °C. It could depend on the preparation of the study, i.e. taping the sensors to the skin, while subjects were minimally dressed. Subjects 5 and 6 had the most stable toe temperatures if to exclude the start of the day. These subjects took off the footwear during the breaks and wore slippers instead. It is difficult, however, to say if the high and relatively stable toe temperature depended on that. The toe temperatures were in average 6 °C lower than foot skin temperatures. Toe temperature changes did not affect considerably thermal sensation of feet as has been shown before (Paper II; Tochihara et al., 1995). It could be related to that the skin temperatures stayed relatively high.

4.8.3 Sweat accumulation in footwear

The sweat accumulation in the footwear was at average 20 g per day and foot (range 10 - 30). Around 2 g of that stayed in the socks. The amount of sweat, that was accumulated in the footwear of subjects 5 and 6 (took off the footwear during breaks) did not differ from others. Sweating seems to affect footwear insulation depending on sweat rate, sweat amount, and probably also absorption capacity and evaporation resistance of the footwear. During sweating tests on a thermal foot model (Paper III) a considerable reduction of footwear insulation was shown. During those tests a sweat rate of 10 g/h was simulated. However, in everyday work situations the sweat accumulation is often not so high, in present study 1.4-6.7 g/h/foot. At these sweat rates the insulation is reduced less, and this results in drier socks and thus more comfortable feet. However, even lower sweat rates (3 and 5 g/h/foot) have been shown to reduce footwear insulation considerably (Paper IV). It should be noted that in the field study some of the sweat did probably evaporate, and some weight gain could be related to the environment (dust, rain).

4.9 A field study at a telecommunication company

Some data was lost, probably due to the strong electromagnetic field near the antennas.

4.9.1 Questionnaire at the end of the day

The observed work times did fit relatively well with work times from the questionnaire. The test persons estimated their work exertion and the time worked at

Table 8. The footwear and sock weight, foot and toe skin temperature (mean (min-max)), air temperature (mean (min)), moisture accumulation, oxygen consumption and thermal sensation in feet (mean over work period (lowest during work period)) data of the subjects, and presence (yes=1, no=0) of wetness and coldness sensations in feet during work reported in the questionnaire after the work period. Data was ranked by foot skin temperature.

Footwear (subject)	Footwear (sock) weight (g/pair)	Foot temp. (°C)	Toe temp. (°C)	Air temp. (°C)	Total moisture accumulation (g)	VO_2	Thermal sensation	Wet	Cold
Shoes (7)	1447 (80)	29.2 (27.8-30.8)	21.5 (17.9-25.3)	8.0 (7.3)	17	0.85	-0.7 (-1)	0	1
WS (2)	1784 (79)	29.9 (28.3-30.9)	19.7 (17.3-22.9)	4.0 (0.3)	33	0.94	2.2 (2)	0	0
WS (3)	2021 (74)	32.7 (31.5-34.2)	22.1 (19.8-25.1)	7.3 (6.7)	24	1.35	0.2 (0)	0	0
WS (4)	1764 (64)	32.7 (31.3-34.3)	27.0 (20.1-33.5)	7.3 (6.7)	60	1.23	2.0 (2)	0	0
WS (1)	1756 (81)	33.1 (32.3-34.6)	28.6 (21.9-33.9)	4.0 (0.3)	44	0.91	1.8 (1)	0	0
WS (5)	1863 (82)	33.2 (30.4-34.6)	29.1 (19.8-33.6)	6.7 (5.5)	28	0.95	1.7 (1)	1	0
WS (6)	2021 (70)	33.2 (30.9-33.9)	30.3 (23.6-32.0)	6.7 (5.5)	60	1.30	1.0 (0)	0	0
WS (8)	1736 (82)	33.4 (29.8-35.5)	31.7 (25.4-35.0)	8.0 (7.3)	51	1.29	1.5 (0)	0	0

Table 9. The footwear and sock weight, foot and toe skin temperature (mean (min-max)), air temperature near body (mean (min)), air velocity (mean (min)), moisture accumulation and thermal sensation in feet (mean over work period (lowest during work period)) data of the subjects, and presence (yes=1, no=0) of wetness and coldness sensations in feet during work reported in the questionnaire after the work period. Data was ranked by foot skin temperature.

Footwear (subject)	Footwear (sock) weight (g/pair)	Foot temp. (°C)	Toe temp. (°C)	Air temp. (°C)	Air velocity (m/s)	Total moisture accumulation (g)	Thermal sensation	Wet	Cold
Varm-varm (6)	1828 (63)	26.7 (25.9-27.1)	Missing	1.9 (-2.4)	9.7 (13.5)	6	0.1 (0)	0	0
WS (3)	1988 (69+104)	27.7 (20.8-31.2)	23.2 (11.0-30.5)	1.5 (-11.5)	3.6 (6.1)	35	0.8 (-2)	0	0
Graninge (5)	1808 (69+143)	29.3 (27.9-31.2)	17.2 (14.9-19.5)	2.1 (-2.1)	9.7 (13.5)	12	-0.1 (-1)	0	0
WS (4)	1982 (54+106)	30.4 (25.9-34.3)	23.4 (9.8-33.7)	3.9 (-0.6)	3.6 (6.1)	56	0.0 (-2)	0	1
WS (2)	1681 (80+100)	30.8 (27.1-34.3)	26.9 (12.7-34.7)	2.9 (-0.6)	3.4 (9.1)	54	0.1 (-2)	0	0
WS (1)	1754 (65+107)	31.4 (28.2-33.8)	17.1 (13.9-20.9)	-4.1 (-10.9)	3.4 (9.1)	63	0.7 (0)	0	0
WS (8)	1910 (67+133)	31.8 (26.7-34.8)	29.6 (18.0-35.2)	3.8 (-5.6)	1.7 (4.6)	94	0.8 (-1)	1	0
WS (7)	1783 (82+165)	32.0 (29.3-34.2)	Missing	8.8 (-1.2)	1.7 (4.6)	39	0.7 (-1)	1	0

certain exertion level in following way: very light in average 1.6 (1-2.5) hours (4 persons), light 2.1 (1-4) hours (7 persons), moderate 1.4 (1.5-6) hours (4 persons), heavy 0.5 (0.5-1) hours (5 persons) and very heavy 0.5 hours (4 persons). Five workers worked outdoors 4-6 hours, one 2-4 hours and two 0.5-2 hours (observed 2.3-5 hours). The length of an average work period outdoors was more than 2 hours for 4 persons, 1-2 hours for 2 and less than 1 hour for one person (observed average 1.8 hours). One did not answer the question. Three persons had 3-5 breaks per day, three had 1-2 and 2 did not have any breaks. The length of a break was estimated to be 0.5-1 hour (3 persons), 15- 30 minutes (1) and less than 15 minutes (2). Two worked once or twice in warm locations, but duration of warm work was less than 15 minutes. The workers were not disturbed by cold (2 persons) or were disturbed just occasionally (6). The workers related the cold sensation in feet to the wind (2 subjects), contact with cold surfaces (2), footwear material, the way how footwear is used and standing still (all 1). The subjects felt to be similar (6) or warmer (2) compared to usual cold season workdays.

The footwear were considered comfortable except by 1 worker and 1 had no opinion. The problems with the footwear were given to be stiff in the cold (1 person), cold feet (1), sweaty feet (2) and wet feet (1). One person slipped during the day, nobody fell.

4.9.2 Foot skin temperatures

The foot skin temperature over time are shown in Figure 14. During colder weather the foot skin temperatures were lower than during warmer weather. There was also a tendency that before lunch the foot, and especially the toe temperatures were lower. This could be related to lower air temperatures before noon, but also to the long dressing time in the morning due to the taping of the temperature sensors to the skin. The subjective responses followed the skin temperatures. The lowest average foot skin temperature was 26.7 °C and this was measured in subject 6 (Table 9). However, his subjective ratings were usually at comfort (0). This subject had also the smallest amount of sweat accumulated in the footwear and sock. Probably due to the influence from the electromagnetic field his foot data recording did stop relatively early and toe temperature data were lost.

The lowest measured foot skin temperature was 20.7 °C (Table 9, Figure 14). This subject (3) had also the next lowest average foot skin temperature (27.7±3.1 °C). His job in the morning consisted of standing on the elevator roof and fastening of new cables to the mast. The highest mean foot skin temperatures were in subject 7 (32.0±1.4 °C, toe skin temperature missing).

The mean difference between the toe and foot skin temperatures was 7 °C. All the subjects had at least once the toe temperatures under 18 °C (data for 2 subjects was lost). Subject 1 had the lowest mean toe skin temperature (17.1±2.2 °C). Subject 4 had the lowest measured toe temperature (9.8 °C). This subject was also the one who in the questionnaire pointed out cold feet. The highest mean toe skin temperature was measured on subject 8 (29.6±5.7 °C). He had also the second highest foot skin temperature, and the highest sweat gain in footwear and socks (94 g). The high foot and toe temperatures of subjects 7 and 8 can be related to the warmer weather and lower air velocity than during other days. These subjects had also relatively high activity throughout the whole day.

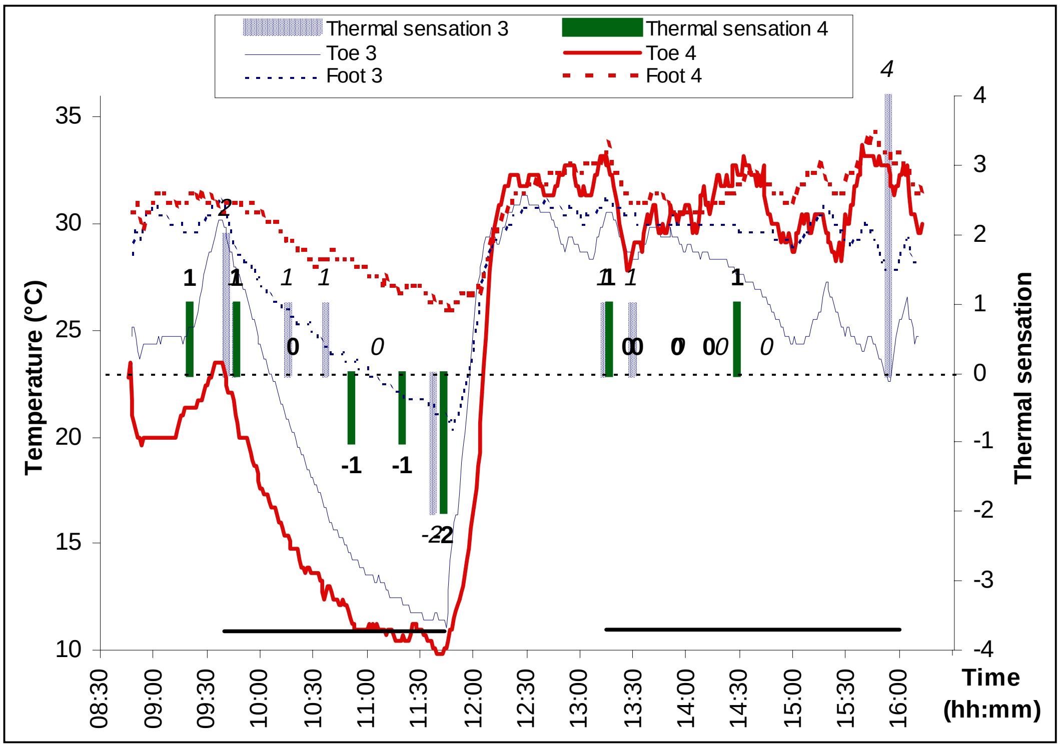

Figure 14. Foot and toe temperatures of subjects 3 and 4. Thick lines at time axis show work periods. Columns and numbers show the thermal sensation in feet (*1* - subject 3; **1** - subject 4) at given time point.

4.9.3 Sweat accumulation in footwear

The total sweat accumulation in the footwear was at average 37 g (6-94 g) per day. Around 4 g of that stayed in the socks. However, the length of the workday varied. The sweat gain in the sock and boot per foot and workday length was 3.7±1.8 g/h (1.1-6.4 g/h). It should be noted that in the field study some of the sweat did probably evaporate, and some weight gain could be related to the environmental factors.

4.10 A field study in dairy farms (PaperVII)

The weather conditions varied during the test period. The coldest outdoor temperature was -11 °C and the warmest days were around +5 °C. Most work was carried out indoors. However, it shifted quite much between various locations and outdoors. The buildings could have big temperature differences, the warmest being the milk-room (even higher than 25 °C), while the cowshed and the fodder storage often had outdoor temperature.

Typical foot and toe skin temperature profiles are shown in Figure 15. During work in the milking parlour the foot and toe temperatures stayed relatively constant. When the work included tasks outdoors or in the buildings with low temperature (near outdoor temperature) they fluctuated more up and down depending on the activity and environmental temperature. During the breaks the workers usually took off the footwear. That resulted in a quick rise in foot, and especially in toe temperatures. However, the return to cold brought a quick drop in temperatures again. One person used a warm air blower between the milking periods to dry the footwear. He was also the one with the highest mean foot skin temperature.

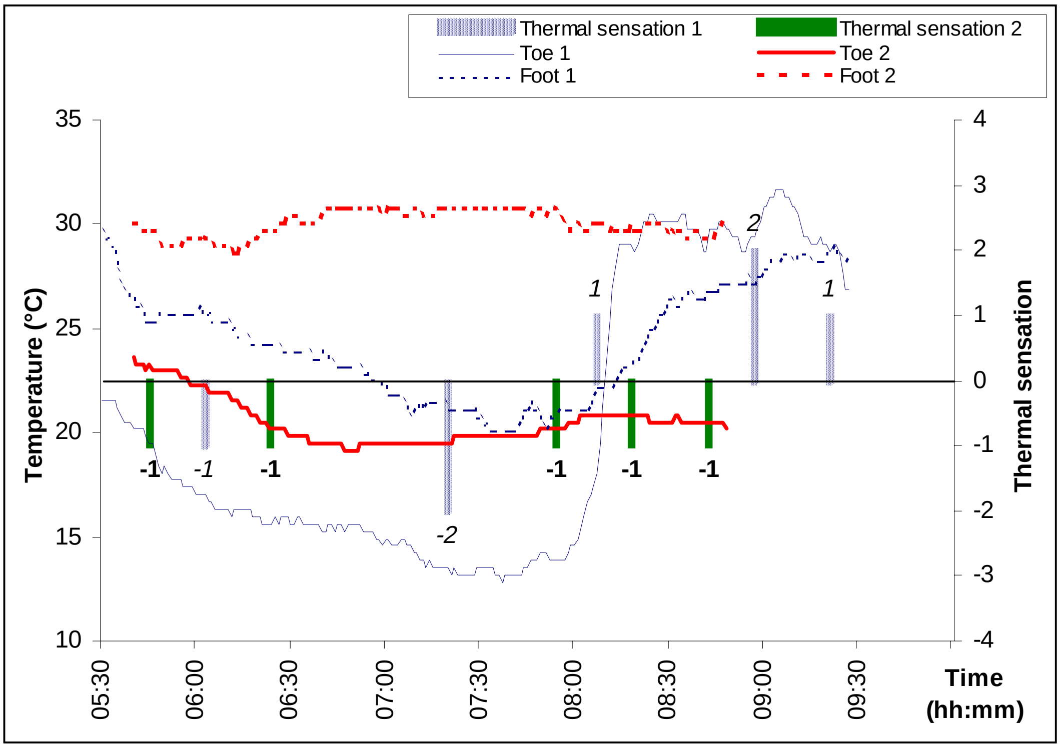

Figure 15. Typical foot and toe temperatures during milking in a milking parlour of another 2 subjects. Subject 1 (a subject with lowest foot skin temperature) finished milking before 8 o'clock, entered a milk room and started other activities (feeding animals etc.). At the same time outdoor temperature started raising and contributing to the temperature raise indoors. The air temperature near the floor was of milking parlour for subject 1 around 4 °C and for subject 2 around 9 °C. Columns and numbers show the thermal sensation in feet (*0* - subject 1; **0** - subject 2) at given time points.

On the average, the toes had 7.3 degrees lower skin temperature than the feet. The mean air temperature near the body was 12.7±4.6 °C. The mean air temperature in the milking parlour near the floor was generally between 5 and 10 °C, in some cases over and in few cases lower. In comparison with a field study at a harbour (Gavhed et al., 1999b) it can be said that at dairy farms the foot and toe skin temperatures stayed considerably lower. Only one person used shoes and his foot and toe skin temperatures were relatively close to these measured at the dairy farms. In another study about high-mast workers (Gavhed et al., 1999a) with lower ambient temperatures (from -0.6 to -11.5 °C), where warm boots were used, the foot and toe temperatures stayed about 1-1.5 °C higher than in farm workers. The lengths of work periods in cold in both cases were similar. Generally, the thermal sensation of the farmers was lower, too. Persons with insulated boots had relatively less complaints on cold feet, however, they responded to wet or sweaty feet in a similar way.

There was a good relationship between low foot skin temperature and farmers response of freezing feet (questionnaire on the day). The correlation was not as good with toe temperatures. The low toe skin temperatures correlated better with the wetness sensation in feet.

The lowest mean foot skin temperature over the whole work period was 24.1±2.6 °C and lowest measured foot skin temperature was 20.1 °C (Figure 15). The same person had also the lowest measured toe temperature (12.8 °C). The subject used rubber boots with steel toe cap and one pair of thin socks. The subject rated the thermal sensation as cool (-2) at lowest. In the questionnaire the subject mentioned that the cold and wet feet were a problem.

The toe skin temperatures of all subjects dropped under 22 °C at least once. The lowest mean toe temperature over the work period was 16.0±1.4 °C (never higher than 21 °C during measurements) and belonged to another person, who used rubber boots with steel toe, 2 pairs of socks and was exposed to 10.9±6.7 °C (-6.6 to 21.4) over the whole work period. That subject had relatively high foot skin temperature (30.2±0.4 °C).

The highest mean foot skin temperature over the work period was 31.6±0.4 °C and for toes 29.1±2.5 °C (different persons). Both of them wore rubber boots with steel toe, and one pair of socks. Both of them had air temperature near body relatively high: 18.9±3.4 (outdoors -1.6±0.6 °C) and 16.6±5.0 °C respectively (outdoors around 5 °C). The first person had mean toe temperature at 21.4±0.8 °C. The second person was feeling hot all over the body during the whole day and had second highest foot skin temperature (31.5±1.0 °C).

Although, the subjects answered “no problems” in general questions, most of them pointed out problems with their footwear: cold feet (7 respondents), sweaty feet (5), wet feet (5), slip risk (3), blisters (2), not enough protection against injuries (2), affected work capacity (1), and bad fit, uncomfortable and affected mobility (1). One mentioned that the footwear becomes stiff and cold at temperatures below -5 °C. One related cold sensation to the steel toe cap.

The workers related the cold sensation in feet to the footwear material (5 subjects), activity change (4), contact with cold surfaces (3), the way the footwear was used (3) and sweating (3). Only one person slipped during the measuring day, but did not fall.

The weight gain of the footwear and socks was on average 27.4 g over an average work period of 3.9 hours. About 6 g of that stayed in the socks. If to consider the weight gain to be related to sweating only, the sweat rate was 4.4±3.3 g/h per foot. However, it could not be determined how much of weight gain was due to sweating or water from outside and dirt, but also how much could evaporate.

4.11 Comparative study of 2 thermal foot models

After finishing the new model (F3), a comparative study was carried out (Kuklane, 1997). The earlier data (Kuklane, 1995) and new data measured with F2 and F3 were analysed. The procedure was kept as close to the previous study as possible.

The same calculation methods were used. The voltage drop was not considered in these calculations.

The separate insulation value of a sock measured with F3 was 0.140 m^2°C/W and with F2 was 0.137 m^2°C/W. The insulation of air layer measured with bare model was for F3 0.088 m^2°C/W and for F2 0.085 m^2°C/W For toe zones of both models it was 0.082 m^2°C/W.

The insulation values of F2 and F3 were close and the insulation values of toes were very similar. The total insulation values for boots had still noticeable differences. The differences between F3 and F2 were less than 0.01 m^2°C/W. In all cases F3 had higher values than F2. The reason could be that the surface of F3 is totally covered with tape but F2 has tape only on measuring wires.

Similar type of difference was present between F2 of this comparative test and F2 of an earlier study (Kuklane, 1995). The differences for certain boots and conditions were even higher than 0.01 m^2°C/W, although they stayed in the limit of 5 % (recommended maximum difference for two tests in whole body manikin testing, (ENV-342, 1997)). These differences could be due to some differences in experimental conditions, e.g. location of the model in chamber and dependence of air velocity on the location. The sock of the same type was used in this study, but not exactly the same one as in the earlier one (Kuklane, 1995).The results from F3 differed from the results of old study more than the limit of 5 %. However, the insulation of toe zone was practically the same.

When the values from the first foot model of the laboratory (Elnäs et al., 1985) were compared to the present results for similar kinds of footwear, were these in the same range. Also air layer insulation measured with bare foot was in the same range (0.084 m^2°C/W).

4.12 Determination of heat loss from the feet and insulation of the footwear (Paper VIII)

Generally, the air layer insulation of bare foot, measured on subjects, was close to the weighted mean. The weighted mean air layer insulation for all conditions was 0.108 m^2°C/W. Latter in its turn was similar to the value measured on a 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 thermal foot model. It makes the dry heat transfer coefficient (h_{dry}=1/I_{dry}) to be 9.3 W/m^2°C.

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 subject at the same temperature could have these values different. It 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 (∅ 13 mm) and its contact with skin. At the same time the values from thermal foot model were remarkably stable.

The differences between subjects in an area insulation and in the 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 test location with higher cooling power and increased natural convection due to higher temperature gradient. However, the toe insulation showed an opposite effect.

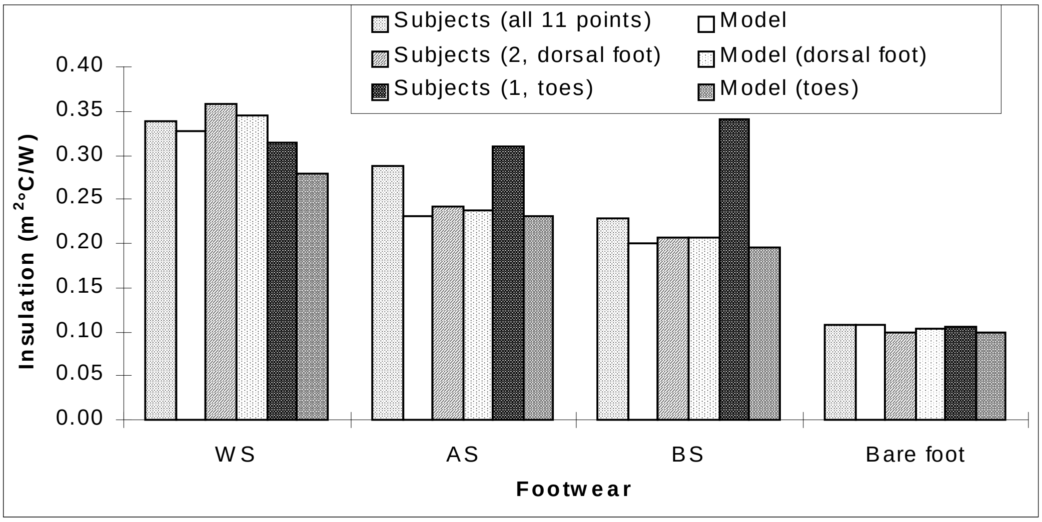

Figure 16. Insulation values from measurements on subjects and on thermal foot model. WS, AS and BS are three types of footwear. The insulation values on subjects are based on all (11) points, 2 points (5 and 6) on dorsal foot and 1 point (1) on big toe.

Figure 16 shows the weighted average footwear and air layer insulation measured on subjects and on thermal foot model as total and for some locations. There were not any significant differences in insulation values measured on humans and thermal foot model for the warmest footwear (WS) at 13 or 19.5 °C in both subjects. However, for AS and BS the results of human and foot model did differ (Figure 16). One subject kept relatively high foot temperature (mean 31.4, toes 32.2 for AS & BS at 19.5 °C). For that subject 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 subject were somewhat higher than those acquired on model. At the same time the insulation values measured on another subject with relatively low foot skin temperatures (mean 29.0, toes 27.8 for AS & BS at 19.5 °C) were much higher and similar to the first subject at 13 °C. The first subject showed even at 13 °C somewhat lower insulation values that were closer to the model values than the second subject at 19.5 °C. The skin temperatures of the first subject at 13 °C were somewhat higher, as well (mean 29.6, toes 28.7 for AS & BS). The biggest differences (31 % for AS and 15 % for BS) were in the footwear without warm lining showing too high insulation compared to the model results. Some differences could be related to the foot shape, its placement in shoe etc., that influence the local insulation. However, the total insulation values should have been similar.

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 16). The insulation measured on dorsal foot of human subjects was in any conditions similar to the value that was got from thermal foot model measurements, while the biggest differences were observed in toes (25 % for AS and 43 % for BS).

The differences between insulation measured on human subjects 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 subjects 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 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. The previous studies also showed that insulation of a garment measured on human subjects could be higher than that measured on the thermal model (Ducharme & Brooks, 1998a; Ducharme et al., 1998b). It was found that the insulation values measured on the subjects were close to these measured on the model when the subjects were at thermal comfort.

The standard (GOST-12.4.185-96, 1996) demands to measure the garment insulation on subjects 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 determined by the standard are not affected by cooling as easily as the extremities. During the insulation measurements of the extremities, e.g. feet, the cooling continues due to various factors including immobility, reduction of blood flow etc., and the temperature gradient can be reduced to very low levels increasing the error. If the effect of personal protective equipment is studied on separate parts of human body then there can be risk, thus of strongly overestimating the insulation of those particular zones that feel thermally most uncomfortable, i.e. do cool most. The footwear insulation measurements can be then recommended to be carried out based on few measuring points which are less affected by cooling, e.g. points 5 and 6 on dorsal foot (Table 6 and Figure 16). However, the insulation measured there will be strongly related to the local insulation that does not certainly reflect the total insulation of the footwear.

On the basis of the results from different trials with 11 sensors there were chosen out minimal number and location of points that is needed for foot insulation determination on human subjects. 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 the points 3 and 4 (r=98.2 %, Table 6). The set of 4 points had correlation of 99.3% (points 2, 3, 4 and 7, Table 6). 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 while the number and location could be critical for some tests, e.g. walking, because of technical and comfort reasons.

4.13 A comparison of two methods of determining thermal properties of footwear (Paper IX)

The methods ranked the footwear in a similar way. The differences between the footwear with and without steel toe cap were minimal. The relatively big difference in relative humidity had practically no effect on thermal properties of footwear. At the same time, the difference in temperature gradient had a considerable effect on it. The gradient had a bigger effect on thin rubber boot (BS and BS2) than on warm footwear (WS and WS3).

All the tested protective footwear for professional use passed the standard test and are classified as cold protective footwear, even the rubber boot. Human tests in climatic chamber with the same rubber boot (with thick sock) at 2 environmental temperatures (Paper II) showed that at +3 °C the boot provided the needed protection, while, at -12 °C the exposure was connected with unacceptable cold and pain sensation. If the cold is defined as any temperature below +18 °C then the thin rubber boot, of course, protects against cold. However, in this case most of footwear are cold protective. The classification of thin rubber boots as cold protective footwear for subzero conditions is highly questionable.

From above mentioned paragraphs came out 3 reasons for modification or change of the thermal testing sections of standard EN 344:

- The requirement is the pass and fail test, and most footwear that is intended for outdoor use could possibly pass the test.
- For use under different cold conditions the demand needs to be based on the actual performance of the different boots such as the insulation values.
- The tests at temperature gradient extremes (BS2 and WS3) within limits allowed by EN-344 (±2 °C) showed that the boot BS can rise in the rank while the boot WS can drop in rank.

It can be supposed that relative humidity has a minimal effect, if any, on the dry thermal insulation values that are measured with the thermal foot model. During the sweat simulation the air humidity has an effect, however, its magnitude will depend on evaporative resistance of footwear.

The thermal foot method should replace the present standard method of footwear thermal testing. In Table 10 both methods are compared from various aspects. However, the thermal foot method needs some additional improvement and standardisation before it can be used as a standard, and more comparative tests with sweat simulation using different models and latest techniques are required (Giblo et al., 1998; Uedelhoven & Kurz, 1998). It can be suggested to have 2 independent parts in standard: dry and wet testing. However, if the patterns of the insulation change due to sweating will be found out, then the change for particular conditions could be estimated from dry values (Paper IV). The proposal for the change of thermal testing section of EN 344 is given in Appendix.

Below are some points that should be considered for a standard development that are based on the tests of the present study series:

- Number of zones on foot model could be chosen freely, however, there should be at least 5 zones (preferably more): the sole, the zone that borders at a level where low footwear (shoes) ends, the zone that borders at a level where half-boots end, the rest of the leg and a guard zone. The latter is not used for calculations, but is needed to avoid the extra heat losses from a previous zone. A separate toe zone can be recommended as the study series showed lower insulation than average in toe zones of well insulated boots. More zones guarantee information on various parts of footwear, e.g. a model had 29 thermally isolated sections (Santee & Endrusick, 1988) and another model had 16 zones (Elnäs et al., 1985).

Table 10. Comparison of the methods.

Aspect	EN 344	Thermal foot model
Evaluation of footwear for cold conditions.	Pass or fail. (Allows better classification than the present formulation of EN 344.)	Allows classification at different levels of insulation for whole footwear and also for footwear parts, e.g. soles, toes etc. From measured insulation it is possible to calculate temperature changes for various environmental conditions.
Evaluation of footwear for hot conditions.	Pass or fail. (Allows better classification than the present formulation EN 344, sections 4.3.5.1 and 5.8).	Allows classification at different levels of insulation for whole footwear and also for footwear parts. From measured insulation it is possible to calculate temperature changes for various environmental conditions.
Evaluation of wet/humid conditions.	Yes, for material (EN 344 sections 4.4.5, 5.12, 4.4.6, 4.5.4, 5.13), not for whole footwear.	Allows simulation of sweating, measuring of insulation reduction due to wetting and of evaporation.
Additional information to the manufacturer.	None.	Can give information on different parts of footwear (discovering weak points in insulation).
Further use of measured data.	None.	Allows a complete evaluation of the thermal properties of footwear. The information can be used in mathematical models for the selection of footwear, calculation of exposure times etc.

- Recommended surface temperature could be 32±2 °C and it should be regulated at the chosen temperature within ±0.5 °C or less. An important feature is that the temperature gradient between surface and environmental temperature should be enough big: at least 20 °C. However, it depends on footwear insulation (see a section below).
- The voltage drop in connection wires should be considered in calculations of heat losses either in measuring program or later in insulation calculations.
- In a test chamber the footwear should be placed in an upright position on a material with good conductivity, e.g. copper/zinc alloy plate.
- The weight of 35 kg should be applied on the model to simulate the compression of the soles by an average person while standing.
- The size of the footwear should be proper for the thermal foot model's size.
- The ambient temperature in test chamber don't need to be determined, but should be chosen for each footwear by needed power input. It should not deviate from set value more than ±0.5 °C. The power to any zone should not be lower than 10 % and not higher than 90 % of maximum power input. For example, at power input of 300-400 W/m^2 the thin rubber boot could be tested at the temperatures around +10 to -5 °C, warm winter boots at around +5 to -20 °C.

- The test should be carried out until the heat losses from thermal foot model have stabilised (ca 90 minutes). The last 10 minutes of stable data should be used for insulation calculations (based on the experience of these study series).
- The use of a standard sock could be useful. It can be recommended to use a thin cotton sock. It doesn't add much to the insulation of the footwear and in the case of sweating tests the cotton sock could work as a distributor of water and results could be easily comparable with dry tests.
- For sweating tests the environmental temperature during testing should be about 10 °C higher than that for dry tests and air humidity should be fixed.
- "Sweat glands" should allow even distribution of water. Recommended amount and location of "sweat glands" could be: on high ankle on both sides, on top of dorsal foot, on top of toes, in the middle of sole.
- Water supply could be maximally 10 g/h, i.e. 2 g/h per "gland" (5 "glands"), for 90 minutes test. This should supply enough water to distribute moisture evenly, but don't turn the footwear into a pool. A peristaltic pump can be used for water distribution.
- The classification if needed should consider about 4 levels of thermal protection, where 2 highest levels should answer for protection at subzero temperatures. However, it can be strongly recommended to use actual insulation value on labelling with adequate information for the users.

4.14 Validation of a model for prediction of skin temperatures in footwear (Paper X)

Big individual differences were present in foot skin temperatures (Papers I and II). Figure 17 shows predicted and measured average dorsal foot skin temperatures for *Paper II* at -11.8 °C. The calculated values differed most at higher environmental temperature (+2.8 °C) and the correlation was lowest there. At lower temperatures the correlation was higher. In *Paper II* for all boots in all conditions r was 0.85 and for 2 colder conditions only it was 0.87. All measured and predicted foot skin temperatures were significantly correlated except AS at +2.8 °C. The reason could be that the combination of activity, environmental temperature and boot insulation made the foot skin temperature reach steady state and exceed the prediction model's limitations. Figure 18 shows the predicted and measured temperature curves for *Paper I*. In this study the r was 0.95. However, the t-tests showed significant differences between measured and predicted values. Figure 19 shows the regression between measured and calculated foot skin temperatures for both studies.

In *Paper II* the predicted temperature curve differed from measured depending on environmental temperature and intermittent activity level. Considerable heat production from walking could explain some differences, especially at the warmest exposure.

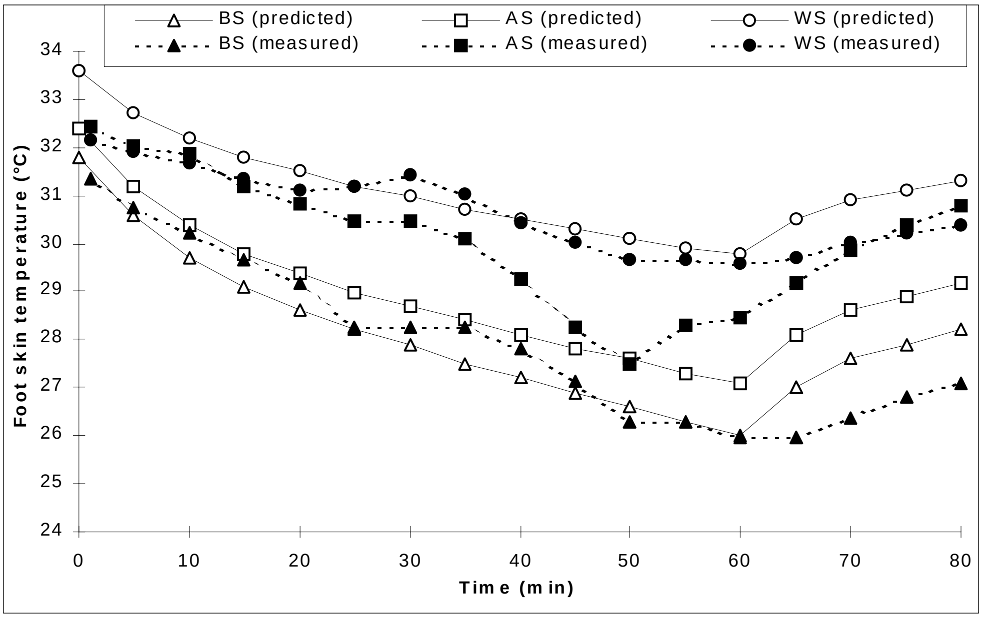

Figure 17. Calculated (predicted) and measured foot skin temperatures at environmental temperature of -11.8 °C.

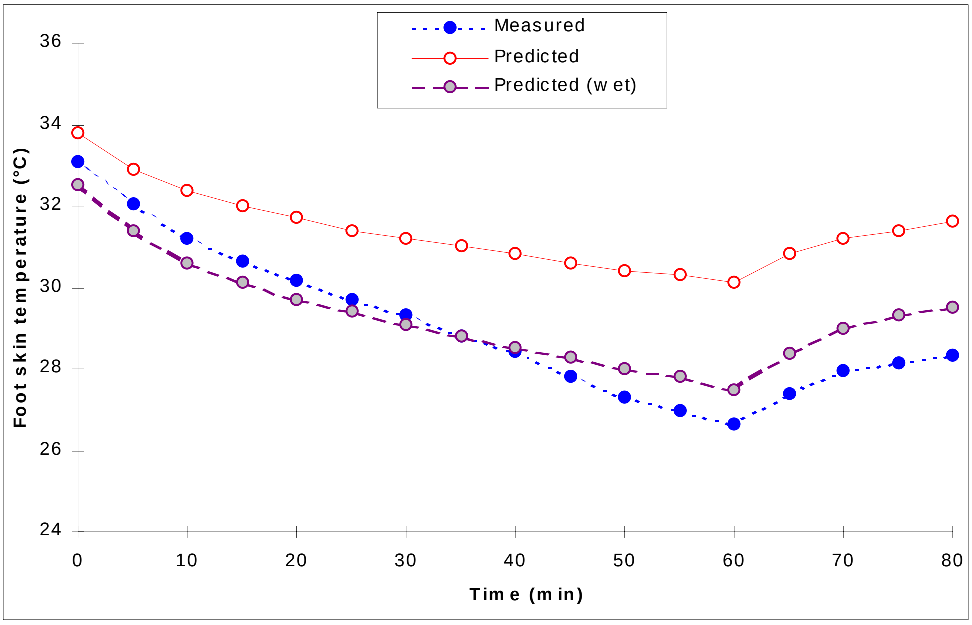

Figure 18. Calculated (predicted) and measured foot skin temperatures at environmental temperature of -10.7 °C (*Paper I*). Predicted (wet) is calculated with estimated insulation reduction for sweating and walking.

Another factor that could influence the results was that for the model development and parameter testing Lotens used insulation values of 0.13 (uppers) and 0.20 (sole) m^2°C/W (Lotens, 1989), while the values measured with thermal foot for similar boot WS were much higher. Lotens probably estimated his insulation values from Santee & Endrusick (Santee & Endrusick, 1988), reducing the values for wetting and motion. Similar reduction of the insulation of the uppers due to sweating and walking was observed in *Paper V*, but that study showed that the insulation of the sole does not reduce during walking. During one hour exposure in cold with relatively low activity the subjects did not have such big sweat rate and insulation reduction due to it could be just very small.

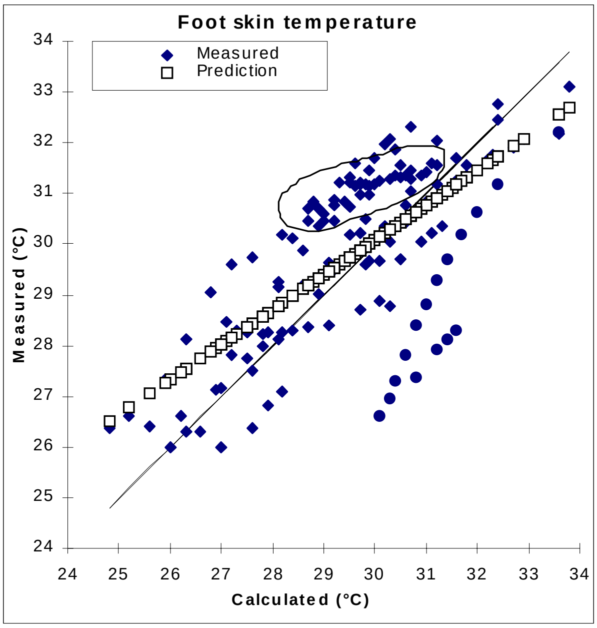

Figure 19. Regression of measured versus calculated foot skin temperatures for both studies (r=0.71). • - values from *Paper I*; in marked area lay mostly the values from warmest exposure (+2.8 °C) of *Paper II*; — - line of identity; "Prediction" show the actual regression points between measured and calculated values.

The underestimated insulation values used in the model development by Lotens can be the main reason why in *Paper I* (constant low activity) the predicted temperature stayed higher for the whole exposure period, using the high measured insulation values. The difference between the predicted and the measured foot skin temperatures was growing proportionally, while warm-up curves were almost parallel. When the insulation was reduced for wetting and walking according to *Paper V* then the paired t-test did not show significant differences any more (Figure 18), while r=96. It shows that the curve patterns are similar (Figure 18) and the main calculation corresponds to measured values, only some parameter values differ.

Most likely the main reason for differences between measured and predicted foot skin temperatures in the *Paper I* were the differences in the estimation of the insulation values. In the *Paper II* the differences were also caused by intermittent activity. At the two colder conditions in *Paper II* the measured and predicted temperatures were at similar levels. Here the two effects seemed to compensate each other to some extent.

When the average foot skin temperatures, based on all three measured points (second toe, lateral heel and dorsal foot), were compared to Lotens' model, then the measured values in both studies were much lower due to considerably lower temperatures of toes and heels. It can be judged that the prediction model does not consider cooling of local points, which are usually critical for exposure length and/or comfort.

5. General discussion

The present study series can be divided into several sections: controlled laboratory tests on human subjects, thermo-physical tests of footwear on thermal foot model and field studies. Each separate part has its function for an entire understanding of footwear function. Laboratory tests with subjects give a picture of physiological and subjective effects that various footwear in combination with different controlled environmental conditions have on people. The thermal foot measurements show the typical changes in footwear thermal properties related to the influence from air temperature, air velocity, motion, humidity and moisture accumulation. The comparative evaluation of human and model tests validates the future use of the method as a standard method from the user point of view. It also gives an information for the manufacturers about their products and allows to improve them. The field studies do show if the reactions in real wear conditions are similar to and can be predicted based on laboratory tests on humans and thermal foot model. If so the outcome of the tests can be used in mathematical models to predict exposure times for defined extremity cooling and in recommending the footwear for use in variety of environmental and work condition.

The whole body thermal insulation affects the local thermal condition and the local insulation has an effect on total thermal comfort (Afanasieva, 1972). This should be considered in any kind of physiological modelling of human thermal status. The present thesis focus on local thermal comfort of feet with special attention on effects of physical changes of footwear thermal properties. The use of data from human tests, thus, should consider the background data, such as activity, environmental factors and clothing insulation on whole body.

Based on the results of the study series, the use of the data from thermal foot model tests can be used more easily. The important factors to consider are environmental temperature and relative humidity, but also the precipitation and ground conditions that can affect footwear from outside (Santee & Endrusick, 1988).

The present study series have shown that the insulation values measured on a thermal foot model did correlate with the foot skin temperatures measured on subjects. Activity helped to keep feet warm. The more insulated footwear restricted loosing of heat (Paper II). Simultaneously, the foot skin temperatures dropped quickly during inactivity. The drop was quicker in footwear with low insulation, however, even in well insulated boots the feet started feeling cold relatively soon. The local effects of insulation (small differences in toes and big in heels for various footwear) became clearly noticeable in measured skin temperatures.

The statistically significant differences in footwear insulation depending on the steel toe cap in footwear have been observed for footwear with low insulation. The footwear with steel toe had slightly higher insulation. However, the insulation differences were not significant from the practical point of view. There were neither statistically significant differences in measured foot skin temperatures nor in subjective responses. The differences were observed in “after effect” of steel toe capped footwear. This effect could be related to slower warm-up of toes in footwear with steel toe cap. Although, the effect shown in subjects was statistically insignificant, at favourable conditions, it can become important from practical viewpoint. After cold exposure the toe temperatures start to warm up after 5-15 minutes of warm break or exercise (Papers I and II; Ozaki et al., 1998; Rintamäki et al., 1992; Rissanen & Rintamäki, 1998; Tochihara et al., 1995). The length of warm breaks is often in that range. If footwear is not taken off the slower warming also keeps toe temperatures at lower levels.

The insulation could be increased with extra pair of thick socks (Paper III). However, stuffing thick socks in tight footwear can have an opposite effect (Paper VIII; Påsche et al., 1990).

Moisture accumulation reduced the footwear insulation considerably. The insulation reduction depended on sweat rate, evaporation-condensation rate, the absorption capacity of the footwear materials and on moisture transport in it (Kim, 1999; Papers III, IV and VI). The evaporation due to the pumping effect in winter footwear, and evaporation in general at subzero temperatures was small (Papers III, IV and VI; Rintamäki & Hassi, 1989b).

In winter boots the insulation reduction due to the walking was relatively small (Papers V and VI). In footwear without warm lining the effect was bigger, e.g. in rubber boots about 30 % (Bergquist & Holmér, 1997; Paper V). The reduction during walking could be related to the effect of increased external convection. In the case of winter footwear with warm lining the pumping effect was probably small because of the tight fit around the calf. The air in the warm lining of these boots stayed relatively still, while in rubber footwear the air could move around more freely thus increasing the internal heat exchange. The combined effects of convection and moisture could reduce footwear insulation up to 45 %.

The different sweat rates affected the insulation decrease. Strong sweating decreased the insulation more. However, when sweating stopped the footwear could gain back some of the lost insulation (Paper IV). The effect seemed to depend on the drying of near layers to the foot, i.e. sock, and in that way reducing conductive heat losses from foot surface to more distant and cooler layers. However, the gain would most probably depend on foot skin temperature (in this study the model surface was kept at 34 °C). It should be slower at lower temperatures due to the smaller temperature gradient that will affect water vapour pressure difference near the foot and distant layers of the footwear. Thus, it is important to change the socks after heavy sweating in order to keep the feet warm.

Without special means for drying the footwear it would often not dry out over night or even the weekend (Paper VI). The multi-layer footwear, from where the insulation layers could be taken out, dried much better than those without such possibility. In the cases, where footwear dryers are not available some other means should be used. In addition to frequent change of socks, that is mentioned above, the use of absorbent materials (compare the old advice to use newspaper!) inside the footwear or creating warm spots with good ventilation and low relative humidity could be recommended. In footwear without an absorbent lining and/or with poor moisture transporting capacity the socks that can absorb moisture well, for example, woollen socks could be used. This way the skin surface stays dry and comfort sensation could be maintained for a longer period.

During standing the contact cooling of soles is a big source of heat losses. The good insulation of soles is thus important. This is taken into consideration in the present footwear testing standard (EN-344, 1992) by relating the test to the sole area. The sole is usually a thicker and stronger region of occupational footwear that should correspond to other demands for mechanical protection of feet according to the standard (EN-344, 1992). However, the insulation of other foot regions is also important. The standard is using a pass-fail test for thermal testing of the footwear and does not discriminate between different protection levels. The test of sole area allows to classify the thin rubber boot as a cold protective footwear. If the cold is defined as any temperature under +18 °C, then a thin rubber boot certainly is a cold protective footwear. However, the same conclusion can’t be drawn for subzero temperatures.

The standard demands that the insoles and insulation layers should be non-removable for the testing and classification. According to the discussion above regarding insulation reduction due to wetting and the length of the drying process, the possibility to take out insulation layers and insoles enhances drying of the footwear. The latter contributes to warmer feet and better foot comfort. However, the effect of removable insulation layers on wearing comfort should be studied further.

The thermal foot method is a more advanced method in comparison with EN-344 (Paper IX). It allows an evaluation of the footwear as an entity, and gives feedback to the manufacturers on footwear as a whole and on separate areas. It also provides useful information to customers and allows the use of the results in prediction models (Paper X; Lotens, 1989) and recommendations for use. A proposal for a new standard method is given in Appendix.

The study has shown that the insulation values from thermal foot measurements were well correlated with the insulation measurements on human subjects (Paper VIII). The results were more close if the subjects were at thermal comfort. If the demand for total and local thermal comfort was not followed, then an uncertain factor influenced the results showing higher insulation measured on human subjects than on thermal model (Ducharme & Brooks, 1998a; Ducharme et al., 1998b; Paper VIII). The extremities were more affected. It introduced the risk of overestimating the insulation in extremities, while testing cold protective clothing on humans, and thus exposing the user to a higher risk.

Thermal sensation of feet and pain sensation from cold in feet correlated well with measured insulation (Paper II). The footwear with high insulation provided better thermal comfort than rubber footwear without special insulation layer. The thermal and pain sensations were well related to foot skin temperatures (Figure 20). Cold sensation is related to foot skin temperature and does not depend on boot type or material (Figure 21). However, the temperature for cold and pain sensations in toes is lower than that for whole foot. It is important to consider the local skin temperatures as a criteria for exposure limitation. Thermal neutrality and warm sensations correspond to similar temperature levels in both toes and in a foot as a whole, while during strong cold sensation the toe skin temperature is about 5 °C lower than mean foot skin temperature. The picture is even more clear with pain: there is no pain while temperatures stay above 25 °C, while first signs of pain appear when toe temperatures are around 15 °C. Further pain sensation grows quickly, without considerable decrease in skin temperature and can become intolerable already before dropping to 10 °C. As the pain and cold sensation during the studies was often connected to toes, then the toe temperature can be recommended to be the limiting criteria for the exposure. At 15 °C the cold receptors seem to be overridden by the pain receptors activity. Cold sensation is present due to the higher temperature in other foot areas.

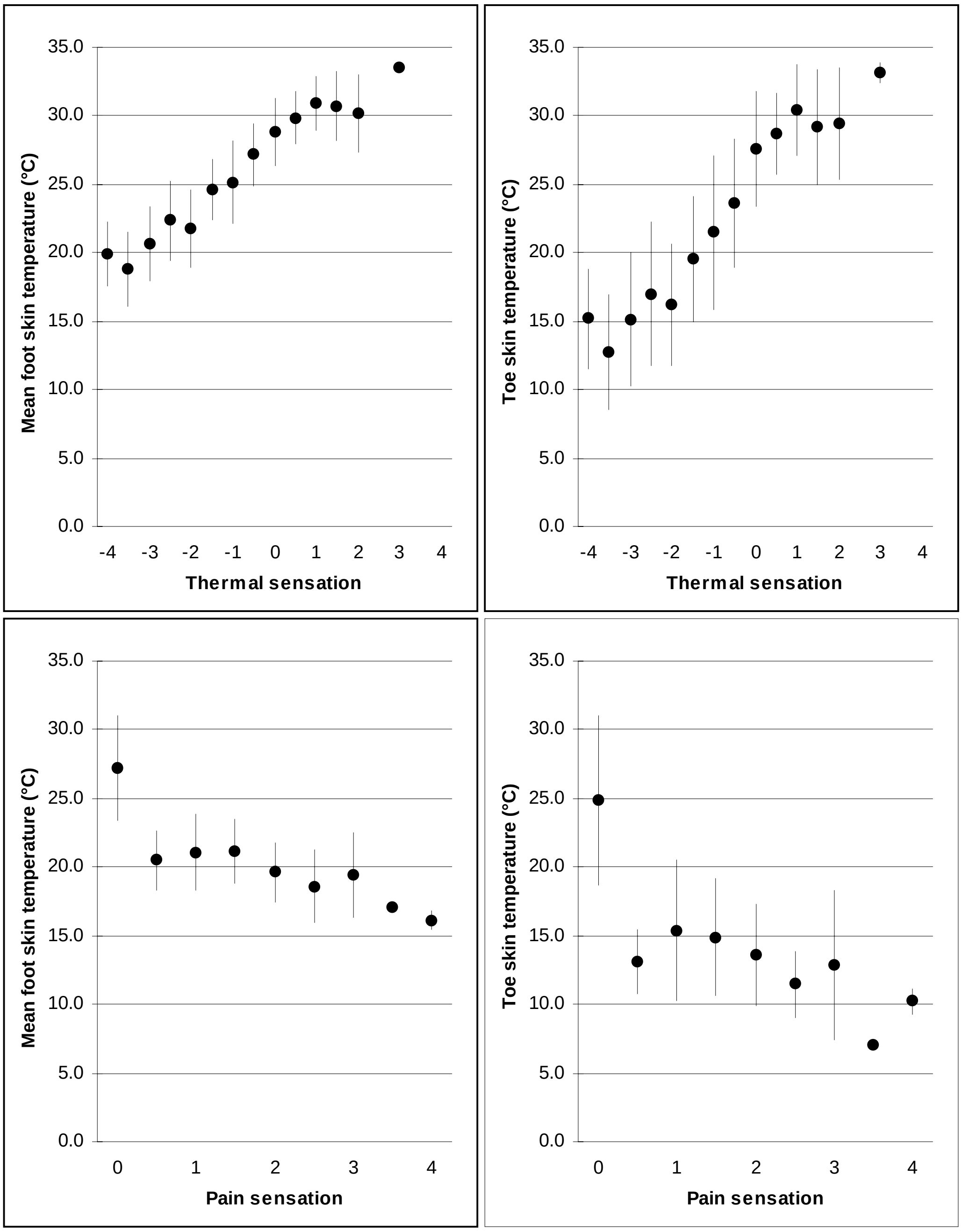

Figure 20. Relationship between thermal and pain sensations and mean foot and toe skin temperatures. The values include ratings during cold exposure, intermittent activity and warm up (Paper II).

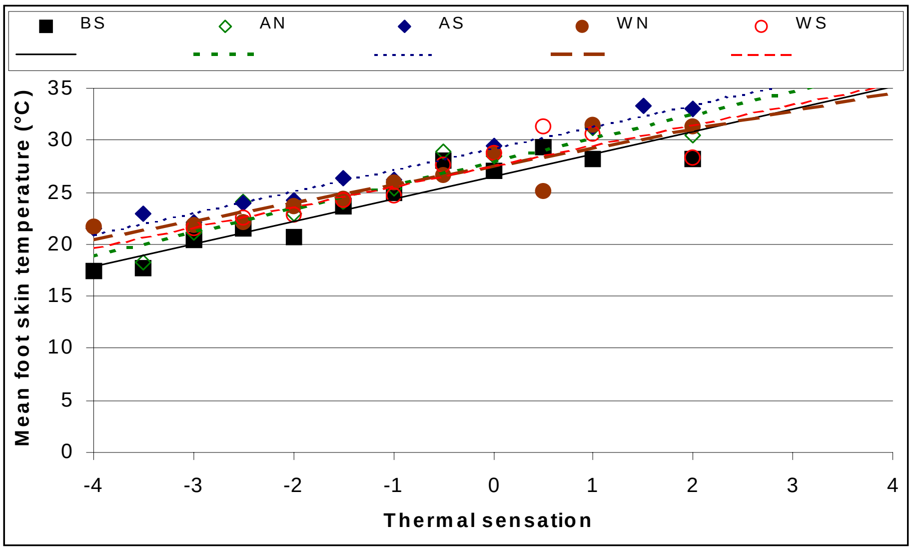

Figure 21. Thermal sensation as a function of mean foot skin temperature for various boots at -12 °C and their linear trendlines.

Figure 22 gives an idea for the choice of footwear based on the criteria of foot skin temperature for two activity levels. The model assumes relatively even temperature and insulation distribution over whole foot surface. For example, temperature interval of 15 to 20 °C corresponds to pain criteria in toes (Figure 20), if the toe zone insulation corresponds to that interval on insulation axes. Based on the study series certain footwear insulation could be suggested for some temperature ranges (Table 11). Footwear insulation reduction due to sweating can be considered according to Equation 4 (Paper IV).

Table 11. Recommended insulation at some temperatures during low activity (around 100 W/m^2).

Air temperature (°C)	Thermal insulation I_{Tr} in m^2°C/W
+15 to +5	$0.20 \leq I_{Tr} < 0.25$
+5 to –5	$0.25 \leq I_{Tr} < 0.30$
-5 to –15	$0.30 \leq I_{Tr} < 0.37$
-15 to –25	$0.37 \leq I_{Tr} < 0.45$
< -25	$0.45 \leq I_{Tr}$

Field studies have confirmed the relevance of the use of the thermal foot method for footwear testing regarding its thermal protection (Gavhed et al., 1999a; Gavhed et al., 1999b; Paper VII). The insulation values are relevant if the footwear is tested in the conditions described in these study series. For the use of these values more broadly comparison with other laboratories is needed. Although, 3 thermal foot models, developed in our laboratory have given similar air layer insulation values and relatively close values for similar boot types, the joint testing would give the validation for the method for use as a standard method. It will show the inter-laboratory differences and differences due to the different model construction.

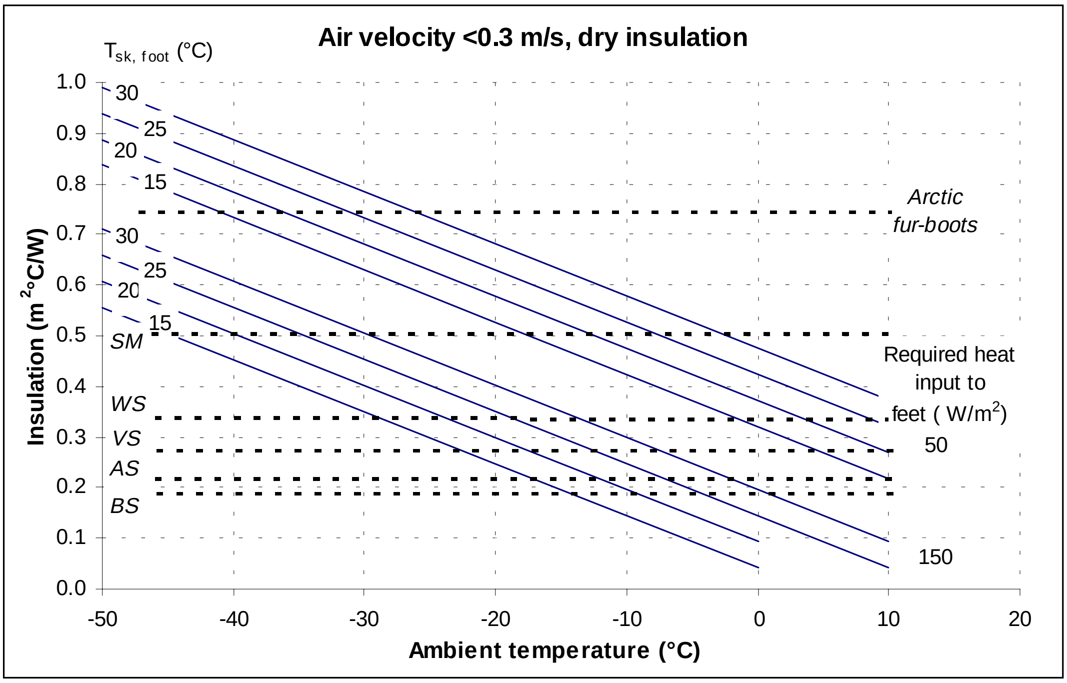

Figure 22. Resultant footwear insulation in relation to required heat input (50 and 150 W/m^2) to feet. Foot skin temperatures ($T_{sk, foot}$) between 25 and 30 °C correspond to thermal comfort without strong sweating response, between 20 and 25 °C allow cold sensation of some degree and between 15 and 20 °C correspond to pain criteria. The figure includes some footwear as an example: BS is a rubber boot without warm lining, AS is a leather boot without warm lining, VS is similar to AS, but with warm lining of nylon fur, WS is a boot of impregnated leather with Thinsulate® and nylon fur lining, SM is a 3 layer boot for extreme cold consisting of 2 felt innerboots and nylon outer layer (Figure 1, Table 4). Arctic fur boot has been measured on human subjects in Russia (Afanasieva, personal communication).

6. Conclusions and recommendations

- There are considerable individual differences in physiological responses to the cold exposure. Thermal sensation in feet is relatively well correlated with mean foot skin temperature in spite of considerable individual variation.
- Cold and pain sensations are connected with locally lowered foot skin temperature, especially in toes and heels. The results from thermal foot measurements point to insufficient insulation in toe parts of cold weather footwear and it could be improved.
- It can be recommended to use local (toe) skin temperature as a criteria for limiting the exposure time.
- The decrease in footwear insulation due to sweating can be measured on a thermal foot model.
- The thermal foot method appears to be a practical tool for thermal evaluation of footwear. The mean error of the method is around 2-3 %.
- The tests on human foot and 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. It can be suggested to use the thermal foot method as a standard method for footwear thermal testing rather than tests on subjects.
- The cooling of the subject is probably the reason, why the measured insulation values from subjects were higher than those measured on thermal model. The effect was bigger in boots with low insulation and at extreme points of the foot, especially in toes.
- The boots with lower insulation had more homogenous insulation distribution than the boots with higher insulation.
- Initial footwear insulation is an important factor to keep feet warm, however, activity of subjects and dryness of footwear influence strongly the foot temperatures.
- The insulation becomes more important factor at lower environmental temperature and with activity: the generated heat is better trapped in boots with higher insulation.
- No significant differences in insulation values between boots with and without steel toe cap were observed for footwear with warm lining. The footwear with steel toe cap but without warm lining had somewhat higher insulation than similar footwear without steel toe. The differences were statistically significant, however, insignificant for practical use.
- Boots with steel toe caps may show an "after-effect" which affects cooling of the feet. This effect can be caused by the higher mass and thermal inertia of steel toe caps.
- A sweat rate of 3 g/h reduces the footwear insulation by 9-19 %. Higher sweat rates (10 g/h) can reduce insulation by 19 to 36 % depending on the initial insulation of footwear. The reduction is bigger in boots with insulation layer. In toes the insulation reduction due to sweating can be about 30 % for boots with lower insulation and about 45 % in boots with higher insulation.

- The insulation reduction stabilises when the balance between sweat rate, and evaporation and sweat transport is reached. Further insulation reduction depends mostly on wetting of insulation layers that increases heat conductivity. This is related to moisture absorption capacity of the footwear; lower capacity is connected with further insulation drop depending on the wetting of the layers straight next to the skin.
- The insulation of the footwear is reduced about 10 % by walking, in thin rubber boots even about 30 %. Sweating and walking together reduce the insulation about 45 %, in toes even up to 55 %.
- Weight reduces insulation of boots. In dry condition the reduction of insulation due to weight is 3-4 %, while in wet condition the insulation of boots with high insulation is diminished by 6-7 % and in boots with low insulation up to 3 %.
- The sole insulation is affected more by weight. In dry conditions the reduction can be 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 is higher. The insulation reduction can be in some boots up to 13-14 %.
- The sole insulation is less affected by walking. The heat losses are diminished by less conductive heat loss and heat generation due to friction, and the insulation of sole can be higher during walking than during standing.
- Less than 7 % of sweat evaporates from the boots while standing still. The evaporation from the winter boots is usually less than 5 %.
- Large amounts of moisture can stay in socks (30 %), thus affecting thermal comfort. Only one sock material was studied and the behaviour of others should be studied.
- Thick socks compared to thin socks add around 5 to 11 % more to total insulation. Footwear without warm lining gains relatively more.
- The present standard method for thermal testing of footwear is a pass/fail test and insufficient as a base for selection of appropriate protection level under different cold and hot conditions. It can be suggested to use the thermal foot method as a standard method for footwear thermal testing in favour of present standard method.
- The measuring conditions and procedure affect the results. For standard use of the method a clear description of experimental procedure is required.
- The insulation reduction for some conditions can be calculated by simple equations.
- It is possible to use the insulation values from thermal foot measurements in model calculations. Lotens' foot model is a good base and it could be modified to take into consideration intermittent activity at various loads and insulation changes due to the moisture concentration and motion.
- During work in cold the low insulation of footwear is considered as a problem resulting in cold feet. The wetness of footwear, mainly due to sweating, is also the source of complaints.
- Better communication between workers and employers could be helpful for purchasing footwear according to the workers' needs. Simultaneously, it requires more knowledge and information on products and insulation requirements in various conditions.

- Footwear insulation of 0.34 m^2°C/W was too warm for ambient temperature of 4 to 8 °C and 0.23 m^2°C/W was not enough. Under the studied climatic and work conditions (harbour) the recommended insulation should be between 0.25 and 0.30 m^2°C/W.
- Footwear insulation of 0.34 m^2°C/W in combination of the chosen socks worked well at -2 to -8 °C (work on high masts). However, more attention should be paid to the cold protection of toes: during low foot activity the toe temperatures dropped relatively quickly at air temperatures of about -10 °C and/or high wind speeds (about 10 m/s).
- Wearing rubber footwear in changing environment (-11 to 25 °C) or during low activity at about 10 °C was connected with low foot and toe skin temperatures.
- Cold feet were one of the biggest source of complaints for farmers regarding their thermal work environment. The next biggest problem was connected to sweaty or wet feet. A connection between low toe skin temperatures and wetness sensation was observed in the use of rubber boots.
- It can be recommended to take off the footwear during breaks and let the feet breath and the socks and boots dry.
- The footwear size should be enough big to fit an extra pair of thick socks. If the space is not enough, the compression reduces insulation and simultaneously restricts blood flow to the feet.
- Felt seems to be a material that maintains insulation well both without and with sweating. It can accumulate much moisture so that the feet stay relatively dry for a longer period. Thick felt insoles (8-10 mm) can effectively restrict contact cooling of soles.
- The possibility of replacing insulation layers improves the drying of the footwear between usage. Removable insoles can be easily taken out and dried between work periods or overnight.
- The footwear should be kept dry. Various types of footwear dryers are available on the market. Absorbent material, e.g. newspaper can be stuffed into the boots for short time periods to remove moisture.

7. Further studies

- More comparative studies between laboratories with different foot models are needed. The models should be tested for dry heat exchange and if possible, also for sweating tests. Such studies should give a broader basis for recommending the thermal foot method as a standard method for footwear thermal testing.
- The comparative studies between thermal models and human subjects should be carried out in order to explain the found differences in insulation values measured on humans and models. Some physiological tests should focus on this problem. The results of the investigation should help to use both physiological data and information from thermal model tests in the mathematical models and working out recommendations for practical use: choice of footwear for certain conditions, exposure limits, taking care of footwear and feet etc.
- The prediction models should be developed further for dynamic conditions considering the insulation change due to motion, wind, moisture accumulation, shifting between environments, and activity. Incorporating a foot skin temperature prediction model into a whole body model could be relevant. The body thermal state data for foot calculations could be acquired from a whole body thermal status model, such as the IREQ.
- The validation tests with thermal foot model with different surface temperatures corresponding to strain levels in humans, e.g. 30 °C comfort, 25 °C onset of cold sensation, 20 °C strong cold sensation and start of pain sensation should be carried out at various environmental temperatures on footwear with various insulation levels. Validation tests on human subjects should be carried out as well. The recorded and calculated heat losses should be related to physiological data connected to heat input to feet, e.g. blood flow at various activity levels. This combination would improve the guidelines for choice of footwear.
- In co-operation with manufactures and users the methodology described in this thesis provides a powerful tool for product development. Testing the footwear for weak points is one part of that work. A second area is determining the specific demands of users in a given job type, on their footwear considering comfort, protection from job hazards and environment of use. Easy-to-use/understand instructions for users should be worked out in order to make the test results practicable to a broader public.

8. Summary

Kuklane, K. *Footwear for cold environments: thermal properties, performance and testing.* Arbete och Hälsa 1999:23.

Present standard on safety footwear (EN 344) checks the insulation only at one point in the shoes by means of measuring the temperature change. A method that uses thermal foot model allows to measure footwear insulation simultaneously at various locations and for whole footwear as well.

In the present work the method of heated foot model was developed further. It is possible to simulate sweating and evaluate reduction of insulation of footwear due to wetting and evaporative heat loss. The conditions with various sweat rates, wear length and foot motion were tested.

Footwear with various insulation levels (from thin rubber boots to thick winter boots) was evaluated. Some footwear was manufactured both with and without steel toe cap and this allowed to study the thermal effect of steel toe cap in different conditions. Comparative studies between various methods (thermal foot model, humans, EN 344) for evaluating footwear thermal properties/insulation were carried out. Field studies were carried out for evaluation of footwear and feet conditions in real wear situation.

The insulation of footwear can vary depending on region and insulation level of the footwear. Heavy winter boots had lowest insulation in toe zone and thin boots had heel zone as the coldest region. Sweat rates of 3 g/h can reduce footwear insulation considerably (9-19 % depending on initial dry insulation). At higher sweat rates (10 g/h) the reduction could be up to 36 %. Combined effects of sweating, walking and wind could reduce insulation by about 45 %. Reduction was bigger in warm winter boots. Only small amount of moisture evaporates from winter footwear during use. Insulation reduction levelled off over longer periods of use. The reduction can be calculated by simple equations.

The thermal foot model gave similar insulation values as measured on human subjects in thermal comfort. The insulation values were used for validation of a mathematical model for foot skin temperature prediction. The results obtained with a thermal foot model give more useful information on footwear than does the present standard for footwear thermal testing. Thus, the thermal foot method is recommended for use as a standard.

A steel toe cap in a footwear seems to have no influence on insulation, but may modify the heat losses from the foot. The influence could be related to the “after effect” that probably depends on the mass of steel toe cap and its thermal inertia.

Some recommendations for use and choice of footwear are given.

Keywords: thermal foot model, sweating, footwear, boots, thermal insulation, cold, foot, skin temperature, thermal responses, pain sensation

9. Sammanfattning (summary in Swedish)

Kuklane, K. *Skyddsskor för kyla: termiska egenskaper, funktion och testning.* Arbete och Hälsa 1999:23.

Nuvarande europeiska standard för test av skyddsskor (EN 344) mäter den termiska isolationen bara i en punkt i skon genom att mäta en temperaturändring. En termisk fotmodell möjliggör mätning av isolationen hos skor både i olika zoner och i hela skon.

I detta forskningsprojektet har metoden med rörlig uppvärmd fotmodell vidareutvecklas. Metoden kan simulera svettning och bestämma ändring i isolation av skor beroende på fukt och värmeförlust genom avdunstning. Betingelser med olika svettningsgrad, mättid och simulerad gång testades.

I projektet undersöktes stövlar med olika isoleringsnivåer (från tunna gummistövlar till tjocka vinterstövlar). Några av stövlarna var tillverkade båda med och utan stålhätta och den termiska påverkan av stålhättan under olika betingelser studerades. Jämförande studier mellan olika metoder genomfördes (termisk fotmodell, EN 344, mätningar på människor). För att bedöma termiska egenskaper hos stövlar användes data från försökspersoner och fotmodell tillsammans. En matematisk modell provades för att förutsäga hud temperaturen på foten. Fältstudier genomfördes för att värdera stövlarnas klimatskydd under verkliga förhållanden.

Skodelarna hade olika isolation beroende främst på tjocklek och material. Varma vinterstövlar hade den lägsta isolation vid tårna medan den kallaste delen av gummistövlar var hälen. Även en låg svettningshastighet (3 g/h) minskade isolationen hos alla stövlar (9-19 % jämfört med den ursprungliga torra isolationen). Vid högre svettningshastighet (10 g/h) minskade isolationen med upp till 36 %. I kombination med svettning, rörelse och vind kunde isolationen hos stövlar minska ca 45 %. Minskningen var störst i vinterstövlar. Isolationsförändringen var stor under de första 2 timmarna av 8-timmars mätning, men blev betydligt mindre efter hand. Avdunstningen var generellt mycket liten från vinterstövlar. Enkla samband för att beräkna isolationsminskningen har utarbetats.

Den termiska fotmodellen gav lika isolationsvärdena som de som uppmättes på människor vid termisk komfort. Värdena kan användas i matematiska modeller för att förutsäga hud temperaturer, exponeringstider och välja fotbeklädnad. Resultat från försök med termisk fotmodell ger mer användbar information än nuvarande standardmetod för termisk provning av skor. Därför kan termiska fot metoden rekommenderas att användas som standard.

Det förefaller som om stålhättan har en påverkan, om än liten, på fotens hudtemperatur och modifierar värmeförlusterna från foten. Påverkan kan relateras till den s.k. “efter effekten”, vilken troligen beror på ståltåhättans stora och termiska tröghet.

Rekommendationer för användning och val av skor gavs slutligen.

Nyckelord: termisk fotmodell, svettning, skyddsskor, stövlar, termisk isolation, kyla, fot, hud temperatur, temperaturupplevelse, smärta.

10. Kokkuvõte (summary in Estonian)

Kuklane, K. *Jalatsid külma keskkonna tarbeks: termilised omadused, funktsioneerimine ja katsetamine.* Arbete och Hälsa 1999:23.

Praegune kaitsejalatsite testimise standard (EN 344) kontrollib soojapidavuslikke omadusi vaid jalatsi ühes punktis, mõõtes temperatuuri muutust. Meetod, mis kasutab termilist jala mudelit, võimaldab mõõta jalatsi soojaisolatsiooni üheaegselt erinevates piirkondades ning ühtlasi ka jalatsi kui terviku soojaisolatsiooni.

Selle uurimuse käigus arendati termilise jala meetodit edasi. Meetodiga on võimalik simuleerida higistamist ja hinnata niiskumisest ja aurustumise soojakadudest põhjustatud soojapidavuse vähenemist. Käesoleva töö käigus katsetati erineva higistamiskiiruse ja -kestvuse ning liikumise (kõndimine, tuul) mõju saabaste soojatakistusele.

Katsetes kasutati erineva soojapidavusastmega jalatseid (alates õhukestest kummisaabastest kuni paksude talvesaabasteni). Mõned jalatsid toodeti nii terasvarbakaitsega kui ka ilma selleta ja see võimaldas uurida terasninamiku termilist mõju erinevates tingimustes. Võrreldi erinevaid katsemeetodeid (termiline jala mudel, katseisikud, EN 344), millega on võimalik hinnata/mõõta jalatsite soojuslikke omadusi/soojaisolatsiooni. Jalatseid testiti ka katseisikutega erinevatel keskkonna temperatuuridel. Saadud andmeid kasutati matemaatilises analüüsis jala naha temperatuuride prognoosimiseks. Jalanõude ja jalgade olukorra hindamiseks tegelikes kasutusoludes teostati mõned väliuurimused.

Kaitsejalatsite soojaisolatsioon võib kõikuda sõltuvalt jalatsi piirkonnast ja saapa soojaisolatsiooni astmest. Soojade talvesaabaste kõige nõrgemini soojustatud piirkonnaks olid varbad ja ilma sooja hoidva kihita saabastel oli selleks piirkonnaks kand. Isegi madalad higistamiskiirused (3 g/h) vähendasid tunduvalt jalatsite soojatakistust (9-19 % sõltuvalt algselt kuivalt jalatsilt mõõdetud isolatsioonist). Kõrgemad higistamiskiirused (10 g/h) tõid kaasa kuni 36 % soojatakistuse vähenemise. Soojaisolatsioon võis väheneda umbes 45 %, kui higistamist kombineeriti liikumisega. Kahanemine oli suurem talvesaabaste puhul. Ainult väike kogus niiskust aurustub talvesaabastest kasutamise käigus. Pikema kasutuse käigus isolatsiooni vähenemine tasakaalustub. Isolatsiooniväärtuse kahanemist on võimalik hinnata lihtsate valemite abil.

Termiline jala mudel andis sarnased isolatsiooniväärtused, nagu on mõõdetud soojuslikus tasakaalus olevatel katseisikutel. Neid väärtusi on võimalik kasutada matemaatilistes mudelites. Katsed termilise jala mudeliga annavad rohkem kasulikku teavet kui praegune jõus olev jalatsite termilise katsetamise standard. Seega võib termilise jala meetodit soovitada kasutuseks standardina.

Näib, et terasvarbakaitse mõjutab jala nahatemperatuuri ja muudab soojakadusid jalast. See mõju võib olla seotud "järelmõjuga", mis tõenäoliselt sõltub teraskaitse massist ja soojainertsist.

Antud on ka soovitusi jalatsite kasutamiseks ja valikuks.

Võtmesõnad: termiline jala mudel, higistamine, jalatsid, saapad, soojaisolatsioon, külm, jalg, naha temperatuur, temperatuuritundlikkus, valutundlikkus.

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Appendix. Proposal for a change of thermal testing section of EN 344

The section numbers here correspond to the actual sections in EN 344 and follow its format. The section numbers that are not available are marked with **X**. *Figures* written in italic refer to the figures in the present thesis.

4.3.5 *Resistance to inimical environments*

4.3.5.1 *Thermal insulation of the whole footwear*

Using the test of section **5.8** the footwear must have a label with total insulation according to section **X** (Labelling).

Table 1. Recommended insulation at some temperatures during low activity.

Air temperature (°C)	Thermal insulation I_{Tr} in m^2°C/W
+15 to +5	$0.20 \leq I_{Tr} < 0.25$
+5 to -5	$0.25 \leq I_{Tr} < 0.30$
-5 to -15	$0.30 \leq I_{Tr} < 0.37$
-15 to -25	$0.37 \leq I_{Tr} < 0.45$
<-25	$0.45 \leq I_{Tr}$

4.3.5.2 *Thermal insulation of the sole complex*

Using the test in section **5.8** the footwear must have a label with the insulation of sole complex according to section **X** (Labelling).

5.X Thermal resistance of footwear material

The test is to be implemented according to an European Standard (EN-31092, 1993). (As it won't be possible to cut out a required size of a test piece from each sample, then it can be recommended to use instead of a standard method another method that is described elsewhere (Nilsson et al., 1996).)

5.8 Determination of thermal insulation

5.8.1 *Test requirements*

Before testing, the samples are to be stored for a minimum of 7 days in the following standard atmosphere:

Temperature 20 ± 1 °C
Relative humidity 65 ± 1 %

For footwear with a multilayer construction the test is implemented on all layers simultaneously, even if these, when removed, are not connected to one another.

5.8.2 ***Principle***

The thermal insulation is measured with a heated full scale model of a foot. Design and construction of the foot must achieve the same constant temperature over the whole foot surface.

The heat input to the foot must be sufficient to maintain a mean foot temperature at any level in the range 30 °C to 35 °C at an ambient temperature, which is at least 20 °C lower. The surface and ambient temperatures should be regulated at the chosen temperature with an accuracy of at least ±0.5 °C.

5.8.3 ***Apparatus***

5.8.3.1 *Foot model,* (see *Figure 2*). Number of zones on foot model could be chosen freely, however, there should be at least 5 zones: the sole, the zone that borders at a level where low footwear (shoes) end, the zone that borders at a level where half-boots end, the rest of the leg and a guard zone. The latter is not used for calculations, but is needed to avoid the extra heat losses from the previous zone.

5.8.3.2 *Standard sock,* of thin cotton/polyester (weight ca 20 g). It shall simulate the interaction between foot, sock and footwear.

5.8.3.3 *Climatic chamber*, the internal air temperature of which can be regulated between +10 °C and -10 °C with an accuracy of ±0.5 °C.

5.9.3.4 *Copper/zinc alloy plate,* of 5 mm thickness, positioned as illustrated in *Figure 3*.

5.8.3.5 Measuring equipment, see annex B

5.8.4 ***Test sample***

The size of the footwear must fit the size of thermal foot model. It must be fitted to the foot in a way similar to the way the footwear is worn.

5.8.5 ***Procedure***

5.8.2.1 *Preparation of test piece*
Use the complete item of footwear as the test piece. Condition it for 7 days at 20 °C ± 1 °C and 65 % ± 1 % r.h.

5.8.2.2 *Test procedure*
The standard sock is donned on footwear.

In a test chamber the footwear is placed in an upright position on a material with good conductivity, e.g. copper-zinc alloy plate.

The weight of 35 kg is applied on the model to simulate the compression of the soles by an average person while standing.

The ambient temperature (T_a) is set sufficiently low to meet the requirements of Annex B. The air velocity is kept at 0.3 ± 0.1 m/s.

When the temperature of the foot and power consumption have equilibrated, the measurements are taken as the average values for a period of 10 minutes.

The resultant thermal insulation is calculated by

$$Q_i = \frac{P_i}{A_i} \tag{1}$$

$$I_{Tr,i} = \frac{T_i - T_a}{Q_i} \tag{2}$$

$$I_{Tr} = \frac{(\overline{T}_s - T_a) \cdot \sum A_i}{\sum P_i} \tag{3}$$

where 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).

The insulation for sole or any other separate zone (equations 1 and 2) and for whole footwear or selected zone group (equation 3) is calculated from the same test results.

The average of two independent measurements are used as the values for the test footwear.

X Labelling

The pictogram of the cold protective footwear, is included so that the performance levels follow the symbol:

X total footwear insulation
X insulation of sole complex
X total footwear insulation during wet test
1 water resistance

Level of performance for total footwear insulation during sweating, is included when the test according to section **5.8** with simulated sweating (5 g/h for 90 minutes) is carried out. Level of performance “1” for water resistance, is included when the water permeability test according to **X.X** is fulfilled.

Y Instructions for use

Instructions for use shall correspond to **EN XXX** Section **X.X**.

Annex A

The test value specifies the performance of the footwear under the test conditions. The actual performance of a footwear, when used, in retaining the heat of the foot is determined by the combined effects of several factors. Such factors are the size and fit of the footwear, foot posture and foot working conditions. Wind and moisture absorption are other factors that may considerably affect the protection value.

At high activity levels more heat is available to the feet, allowing them to stay warmer at a given insulation level. The variation between individuals in terms of providing and controlling foot blood flow is great: Figure A1 gives an indication of the required, resultant insulation level for the maintenance of warm feet as function of ambient temperature and activity level.

This information may serve as a guideline for the selection of appropriate protection class.

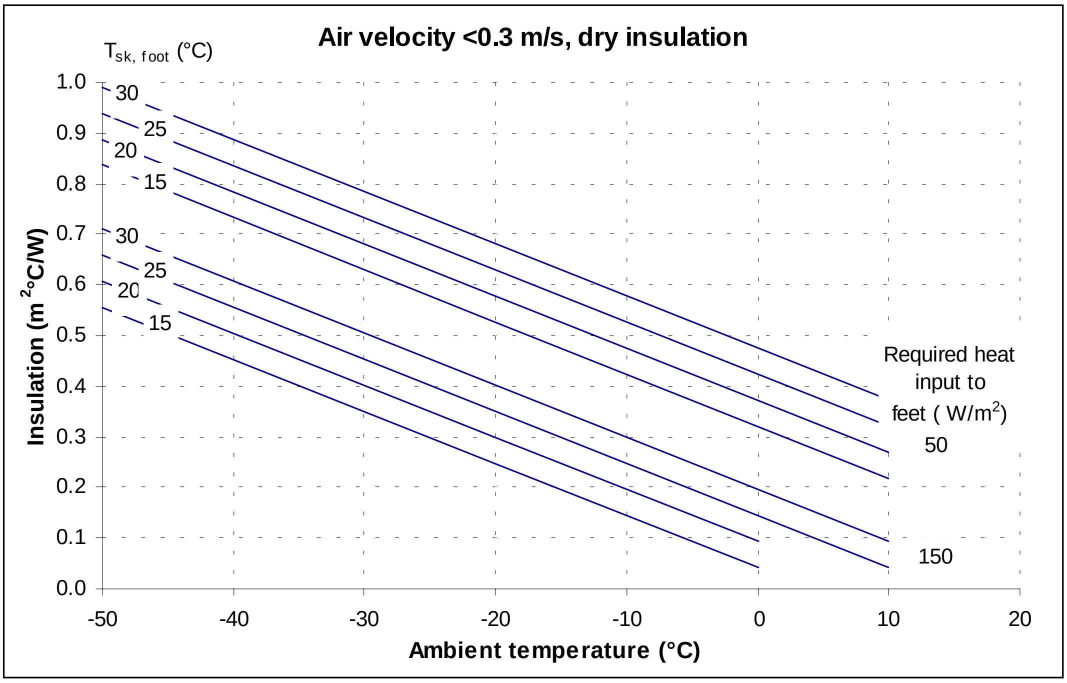

Figure A1. Insulation vs. ambient temperature.

Annex B Description of method

B 1 Principle

Insulation of a footwear is determined by measuring the power required to maintain a constant temperature gradient between the surface of a heated, full-scale foot model and the ambience.

B 2 Definitions

B 2.1 Thermal insulation is the resistance to dry heat transfer via convection, radiation and conduction.

B 2.2 Total insulation (I_{Tr}) is the resistance to dry loss from the foot, which includes the resistance provided by the footwear and the air layer around the dressed model.

B 2.3 Foot skin temperature (T_i) is the mean surface temperature of the measuring zone of the foot.

B 2.4 Foot skin temperature ($\bar{T}_s$) is the mean surface temperature of all measuring zones of the foot that are used for insulation calculation.

B 2.5 Air temperature (T_a) is the mean temperature of the air in the climatic chamber.

B 2.6 Foot heat loss (Q_i) is the measured power supply to the measuring zone of the foot during steady state.

B 3 Apparatus

B 3.1 *General*

In principle thermal insulation can be determined with any apparatus, which can measure and control the temperature of the surface of the foot and the heat loss from the foot. The foot can be made of any suitable material (e. g. plastic, copper, aluminium).

Selection of temperature sensors and heating elements and their application and integration into the foot model is not critical as long as the performance of the apparatus complies with clauses **B 3.2** to **B 3.5**.

A more detailed description of the size, form and shape of the foot is required, since these factors significantly contribute to the variation in measured values.

B 3.2 *Foot model*

Requirements: The size of the footwear should be proper for the thermal foot model's size.

The foot is heated so as to provide a uniform surface temperature.

The foot should consist of at least 5 measuring zones: the sole, the zone that borders at a level where low footwear (shoes) end, the zone that borders at a level where half-boots end, the rest of the leg and a guard zone. The highest zone on the foot (upper calf) is used as a guarding zone and is heated similarly to the foot. The latter is not used for calculations, but is needed to avoid the extra heat losses from previous zone. A separate toe zone can be recommended. More zones guarantee information on various parts of footwear.

A flexible joint at the ankle and toes is recommended as it allows to put on footwear of proper size easier. However, other solutions are also available, for example, foot consisting of two parts: foot and leg with heel, that can be inserted into footwear and connected easily.

B 3.3 *Power supply*

Requirements: Power to the foot shall be measured so as to give an accurate average over the period of the test. The accuracy of the power measurement must be within 2 % of the reading for the average power for the test period.

The foot is heated by a low-voltage DC-power supply. Power supply should be stabilised and provide a constant voltage output (± 1 %).

B 3.4 *Heating elements*

The surface of the foot is covered by densely wired resistance wires. The layer of wires is coated by plastics, approximately 0.2 mm thick.

B 3.5 *Surface temperature*

Requirements: Temperature distribution over the foot surface must be constant, with no local cold or hot spots. The recommended setpoint for mean skin temperature is in the range 30 °C to 35 °C. Local deviations from the controlled mean skin temperature should not exceed ± 0.5 °C. Temperature uniformity must be repeatedly (every year, after repair etc.) checked with a infrared imaging system or equivalent method.

Temperature sensors must be imbedded in the surface layer, not to interfere with the fitting of the test footwear.

Temperature of the foot surface is measured by resistance wires. The sensor wire is taped to the surface in a manner that allows for a representative measure of mean foot surface temperature including all significant areas (toes, sole, dorsal foot, ankle, heel).

B 3.6 *Climatic chamber*

Requirements: The foot shall be placed in a chamber that can provide uniform climatic conditions. Spatial and temporal temperature deviations must be within ± 0.5 °C and relative humidity within ± 1 %.

Mean radiant temperature should not be more than 0.5 °C different from mean air temperature. Mean air velocity in the test zone shall be at 0.3 ± 0.1 m/s.