

The Use of Footwear Insulation Values Measured on a Thermal Foot Model

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The use of physiological data from human tests in modelling should consider background data, such as activity, environmental factors and clothing insulation on the whole body. The present paper focuses on local thermal comfort of feet with special attention on the effects of physical changes of footwear thermal properties. An alternative test method is available for footwear thermal testing besides the standard method. The possibility to use insulation values acquired on a thermal foot model in practice is shown here. The paper describes the correlation between cold and pain sensations, and foot skin temperatures of the subjects and relates these to insulation measured on a thermal foot model. Recommendations are made for footwear choice according to environmental temperature.

thermal foot model cold protective footwear thermal insulation cold exposure limit
thermal sensation pain sensation

1. INTRODUCTION

The whole body thermal insulation affects the local thermal condition and local insulation has an effect on total thermal comfort [1]. This should be considered in any kind of physiological modelling of human thermal status. The present paper focuses on local thermal comfort of feet with special attention on the effects of physical changes of footwear thermal properties. The use of data from human tests, thus, should consider background data, such as activity, environmental factors and clothing insulation on the whole body.

The thermal foot model is a physical model shaped like a human foot. It can be used to measure insulation of socks and footwear. Surface temperature of the model is kept constant, e.g., at 34 °C. Power input to the model (heat loss) is recorded. From the gradient between model surface and ambient temperature, and heat loss per area it is possible to calculate thermal insulation.

Based on the results of several studies, data from thermal foot model tests can be easily used for evaluation and choice of footwear. The

important factors to consider are environmental temperature and relative humidity, but also precipitation (rain, snow) and ground conditions that can affect footwear from the outside [2].

2. AVAILABLE INFORMATION FROM THERMAL FOOT STUDIES

Studies have shown that insulation values measured on a thermal foot model correlated with foot skin temperatures measured on subjects. Activity keeps feet warm. Well-insulated footwear restricts heat loss [3]. Simultaneously, foot skin temperatures drop quickly during inactivity. The drop is quicker in footwear with low insulation, however, even in well-insulated boots feet cool while standing still. The local effects of insulation, e.g., in the toes and heels, become clearly noticeable in measured skin temperatures. After cold exposure toe temperatures start to warm up after 5–15 min of a warm break or exercise [3, 4, 5, 6, 7, 8]. The length of warm breaks

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is often in that range. If footwear is not taken off, the slower warming due to footwear mass and insulation keeps toe temperatures at lower levels.

Insulation can be increased with an extra pair of thick socks [9, 10]. However, stuffing thick socks in tight footwear can have an opposite effect [11, 12].

Moisture accumulation reduces footwear insulation considerably. A reduction in insulation depends on sweat rate, evaporation-condensation rate, absorption capacity of footwear materials, and on moisture transport in them [10, 13, 14]. Uedelhoven, Kurz and Rösch [15] have explained moisture transport out from footwear. Evaporation due to the pumping effect in winter footwear, and evaporation in general at subzero temperatures are small [10, 13, 14, 16].

In winter boots the reduction in insulation due to walking is relatively small [14, 17]. In footwear without warm lining the effect is bigger, e.g., in rubber boots it is about 30% [17, 18]. 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 is probably small because of the tight fit around the calf. The air in the warm lining of these boots stays relatively still, while in footwear without lining the air can move around more freely thus increasing the internal heat exchange. The combined effects of convection and moisture can reduce footwear insulation up to 45% [17].

The different sweat rate affects the decrease in insulation. Strong sweating decreases the insulation to a larger degree. However, when sweating stops footwear can regain some of the lost insulation [13]. The effect seems to depend on the drying of the layers next to the foot, i.e., the sock, and in that way reducing conductive heat loss 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 was kept at 34 °C). It should be slower at lower temperatures due to the smaller temperature gradient that will affect the difference in water vapour pressure near the foot

and the distant layers of the footwear. Thus, it is important to change the socks after heavy sweating in order to keep feet warm.

Without special means for drying footwear it would often not dry out overnight or over a weekend [14]. Multi-layer footwear, from which insulation layers can be taken out, dries more easily than that without such a possibility. Where footwear dryers are not available some other means should be used. In addition to frequent changes of socks, using absorbent materials (age-old advice on using newspapers!) inside the footwear or creating warm spots with good ventilation and low relative humidity can be recommended. In footwear without an absorbent lining and/or with poor moisture transporting capacity, socks that can absorb moisture well, e.g., woollen socks, can be used. In this way the skin surface stays dry and comfort sensation can be maintained for a longer period.

3. STANDARD METHOD (prEN-344:1999) [19]

When standing, contact cooling of soles is a big source of heat loss. Good insulation of soles is thus important. This is taken into consideration in the present footwear testing standard (prEN-344:1999) [19] by relating the test to the sole. The sole is usually a thicker and stronger region of occupational footwear that should correspond to other requirements for mechanical protection of feet according to the standard [19]. However, insulation of other foot regions is also important. The standard uses a pass-fail test for thermal testing of footwear and does not discriminate between different protection levels. The test of the sole area allows classifying a thin rubber boot without insulating lining as cold protective footwear. If the cold is defined as any temperature under +18 °C, then it certainly is cold protective footwear. However, for subzero temperatures, the same conclusion is not true. This does not mean that such boots cannot be worn in the cold, with extra sock insulation they can provide adequate protection.

The standard demands that the insoles and insulation layers should be non-removable for testing and classification. According to the thermal model tests on the reduction in insulation due to wetting and the length of the drying process, the possibility to take out insulation layers and insoles enhances the drying of the footwear. The latter contributes to warmer feet and better foot comfort. Simultaneously, the effect of removable insulation layers on wearing comfort should be considered.

The thermal foot method is a more advanced method in comparison with prEN-344:1999 [20]. It allows an evaluation of footwear as an entity, and gives feedback to the manufacturers on footwear as a whole and on its separate areas. It also provides useful information to customers and makes it possible to use the results in prediction models [21, 22] and in recommendations for use. The footwear can also be tested with socks to evaluate a whole footwear system for various conditions. Therefore, a new standard method can be recommended.

4. INSULATION FROM THERMAL FOOT METHOD RELATED TO HUMAN STUDIES AND PRACTICAL USE OF INSULATION DATA

A study has shown that insulation values from thermal foot measurements were well correlated with insulation measurements on human subjects [23]. The results are closer if the subjects are at thermal comfort. If the demand for total and local thermal comfort is not followed, then some factors influence the results showing higher insulation measured on human subjects than on a thermal model [23, 24, 25]. The insulation value for extremities is more affected probably due to the fact that they cool most.

The effect could be related to moisture/sweat in a liquid form around and under a heat flux sensor, i.e., on skin surface and in clothing. Wissler and Ketch [26] show a measurement error that gives 15–20% lower heat loss during the use in water.

Ducharme, Frim and Tikuisis [27] describe a similar type of error related to the effect of thermal resistance of heat flux discs. It is known [28, 29] that highly conductive surfaces increase the measuring error. Also, uneven contact surface [29], especially during human tests on extremities (feet, hands) caused by insufficient even contact area, motion, etc., increases the errors. Local cooling of extremities, e.g., toes and heels, makes these areas more liable to condensation, due to the fact that lower water vapour pressure moisture in footwear moves towards these areas. It can introduce the risk of overestimating 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 the cold in feet correlate well with measured insulation [3]. Footwear with high insulation provides less thermal strain than footwear without a special insulation layer. Thermal and pain sensations are well related to foot skin temperatures (Figure 1). Cold sensation is related to foot skin temperature and does not depend on boot type or material (Figure 2). However, the temperature for cold and pain sensations in the toes is lower than that for the whole foot. It is important to consider local skin temperatures as a criterion for limiting exposure. Thermal neutrality and warm sensations correspond to similar temperature levels in both the toes and in the foot as a whole, while during a strong cold sensation toe skin temperature is about 5 °C lower than mean foot skin temperature. The picture is even clearer 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 a considerable decrease in skin temperature and it can become intolerable already before dropping to 10 °C. As the pain and cold sensation during the studies was often connected with the toes, then toe temperature can be recommended to be the limiting criteria for exposure. At less than 15 °C the activity of cold

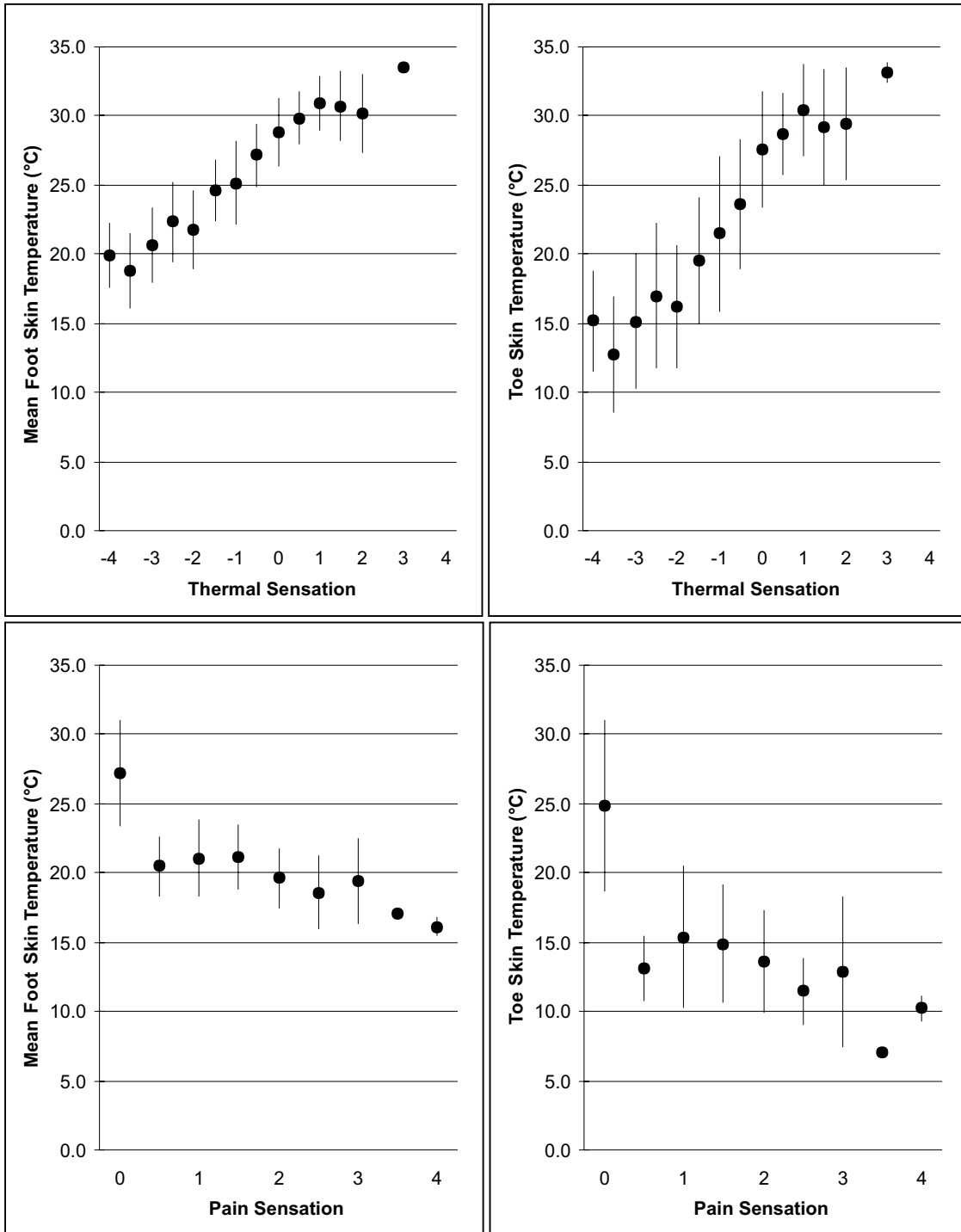


Figure 1. Relationship between thermal and pain sensations and mean foot and toe skin temperatures. The values include ratings during cold exposure, intermittent activity and warm up [3].

receptors seems to be overridden by pain receptors, and the cold is probably still felt due to the higher temperature in other foot areas. Similar temperature ranges were reported by other studies, too [8, 30, 31].

Figure 3 gives an idea on 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.

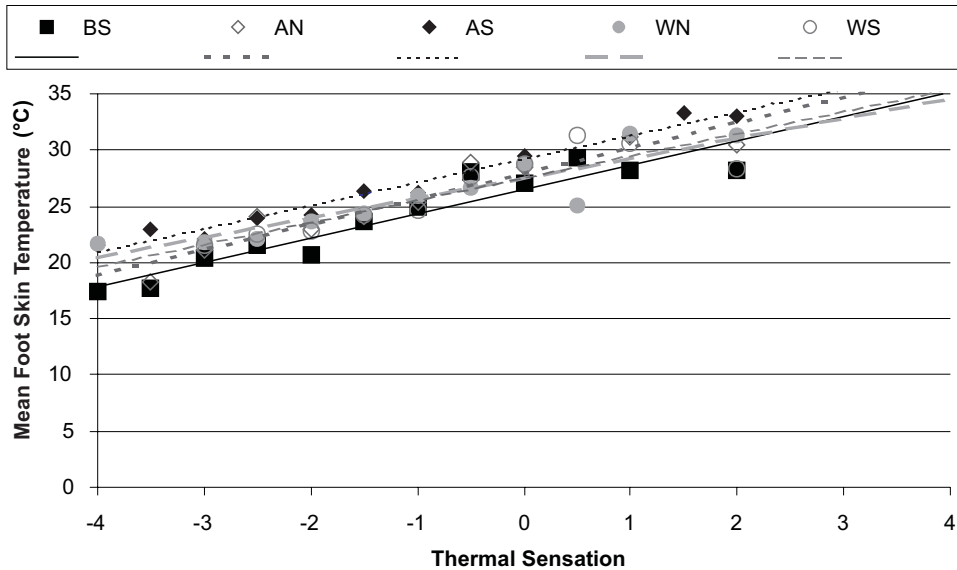


Figure 2. Thermal sensation as a function of mean foot skin temperature for various boots at -12°C and their linear trendlines. Notes. BS—a rubber boot without lining; AN, AS—leather boots without lining; WN, WS—winter boots.

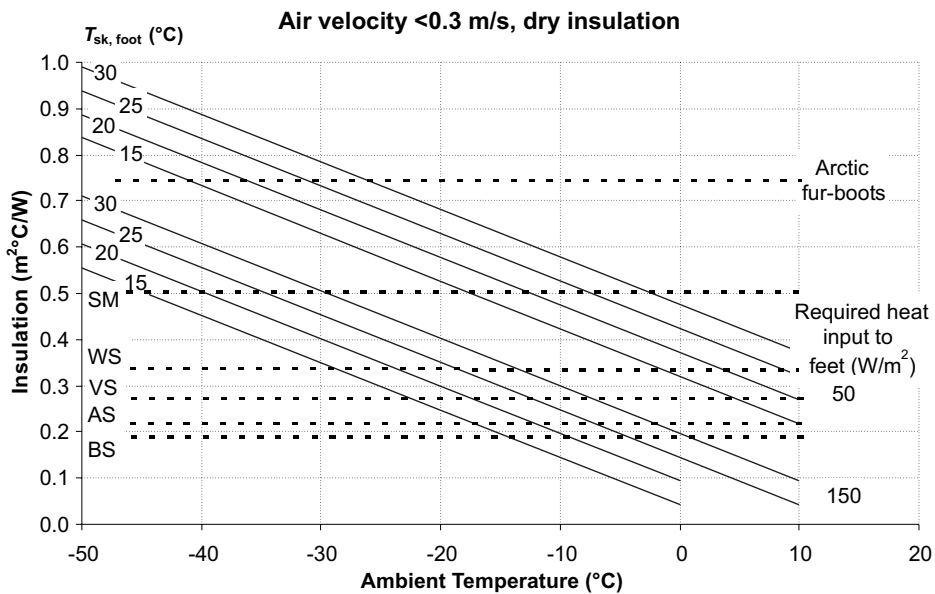


Figure 3. Resultant footwear insulation in relation to required heat input (50 and 150 W/m^2) to feet. Foot skin temperatures ($T_{sk, foot}$) between 25 and 30°C correspond to thermal comfort without strong sweating response, between 20 and 25°C allow cold sensation of some degree and between 15 and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

For example, the temperature interval between 15 and 20°C corresponds to pain criteria in the toes (Figure 1), if the toe zone insulation corresponds to that interval on the insulation axes. Based on the study series certain footwear insulation can be suggested for some

temperature ranges (Table 1). In the future, the temperature and insulation ranges may need to be corrected after additional validation studies. The reduction in footwear insulation due to sweating can be considered according to the equations in Kuklane et al. [13].

TABLE 1. Recommended Footwear Insulation to Minimise Thermal Strain at Some Temperature Ranges During Low Activity (Around 100 W/m²).

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	$0.45 \leq I_{Tr}$

Any thermal situation is modified by several factors: temperature, humidity, wind, radiation, clothing (footwear and socks) material and most strongly by activity (heat production, sweating). Therefore, it may be difficult for the general public to use the guidelines. It is very clear what tear resistance or protection from impact is. However, it is always more difficult with clothing thermal protection as it has not only to protect from (cold) temperatures that may vary but it also has to avoid overheating during high activity, i.e., keep any thermal strain at tolerable limits, allow mobility to carry out the job and possibly fit with any other protection against any other hazardous factors (chemical, biological).

If there is a standard test for insulation measurements and all cold protective footwear will have a label with an insulation value then it will be possible for everybody to choose other boots with higher or lower insulation if they feel too cold or warm. In the same way socks can be selected and changed if their insulation is known. This experience could help the general public to understand the guidelines, too.

On the other hand, people who choose and buy cold protective clothes for workers in their companies benefit directly from the figure and the table. They know the work tasks, approximate activity levels, work periods and possibly even environmental parameters (work in cold stores), and therefore they will have support in choosing proper footwear.

Field studies have confirmed the relevance of the use of the thermal foot method for footwear testing regarding its thermal protection [11, 32,

33]. Insulation values are relevant if footwear is tested in the conditions described in the study series. To be able to use these values more broadly, a comparison with other laboratories is needed. A study like that carried out lately [34]. Although the three thermal foot models developed in our laboratory have given similar air layer insulation values and relatively close values for similar boot types, there were observed considerable differences between some models from different laboratories. As a matter of fact the study raised more questions than it answered. Further joint testing should address those questions and differences and validate the method for use as a standard method.

Hopefully, broader use of the method will help to meet the requirements for professional footwear, enhance footwear choice, and thus improve user performance [35]. As a result, the risk of cold injuries and related diseases [36, 37, 38] could be reduced.

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