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Validation of a Model for Prediction of Skin Temperatures in Footwear

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Abstract. A model for foot skin temperature prediction was evaluated on the basis of 2 experiments on subjects at various environmental temperatures (light seated manual work at − 10.7°C (*Study 1*), and a short walking period in combination with standing and sitting at +2.8°C, − 11.8°C and − 24.6°C (*Study 2*), with boots of 3 insulation levels. Insulation of the footwear was measured on a thermal foot model. Predicted and measured data showed a relatively good correlation (r=0.87) at the 2 colder conditions in *Study 2*. The environmental temperature of 2.8°C was not low enough at the chosen activity for a considerable foot skin temperature drop. In *Study 1* the predicted temperature stayed higher for the whole exposure period and the difference between the predicted and the measured foot skin temperatures grew proportionally with time, while subsequent warm-up curves at room temperature were almost parallel. In *Study 1* the correlation was 0.95. However, the paired *t*-test showed usually significant differences between measured and predicted foot skin temperatures. The insulation values from thermal foot measurements can be used in the model calculations. Lotens' foot model is lacking activity as direct input parameter, however, the blood flow is used instead (effect through T_{core}). The Lotens foot model can give reasonable foot skin temperature values if the model limitations are considered. Due to the lack of activity level input, it will be difficult to make any good estimation of foot skin temperature during intermittent exercise. The rate of the foot temperature recovery after cold exposure was somewhat overestimated in the model - the warm-up of the feet of the subjects started later and was slower in the beginning of the warm-up than in the prediction. It could be useful to develop the model further by taking into consideration various wetness and activity levels.

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Introduction

Local cooling of extremities is often the limiting factor during cold exposure. 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.

The purpose of this study was to validate predictions with the model using actual measurements on subjects exposed to cold environments. The aim of the study was to check how well the insulation values that were measured on the thermal foot model fit into the prediction model. A good fit could provide better basis for the choice of footwear for various cold conditions.

For this evaluation, data from two studies with subjects (*Study 1*-Kuklane et al., 1999; *Study 2*-Kuklane et al., 1998) were available. Values for footwear insulation were obtained from measurements with a thermal foot model (Kuklane et al., 1999; Kuklane & Holmér, 1998).

Methods

Thermal foot model

The footwear insulation of boots of size 41 was measured on a thermal foot model (Kuklane et al., 1999; Kuklane & Holmér, 1998). The foot model is divided into 8 zones. Surface temperature and power to each zone is controlled separately with a regulation computer. Heat losses from each zone are recorded. Knowing heat losses, zone areas, and surface and ambient air temperatures it is possible to calculate insulation values for each zone and for whole footwear.

The same type of sock, that the subjects used, was also used on the thermal model. The ambient temperature was chosen to be at least 20°C lower than the surface temperature of the model (usually more than 30°C) to guarantee a sufficiently big temperature gradient and heat losses in order to reduce the measuring error. During the tests the foot model stood in an upright position. Each boot was tested twice. The limit difference of the two runs had to be less than 0.01 m^2°C/W. If the difference was greater, an additional test was carried out until two values satisfied the demand. However, in most cases two runs were sufficient. The averages of the two values were used in the analysis.

Total insulation was defined as the insulation from toes to ankle according to the formula:

$$I_{t,r} = (\bar{T}_s - T_a) / (\Sigma P_i / \Sigma A_i),$$

where P_i-power to each zone, A_i-area of each zone, $\bar{T}_s$-mean surface temperature and T_a-ambient air temperature.

The measured insulation values for uppers and soles and weight of the boots are shown in Table 1.

Studies on subjects

The studies on subjects were carried out in the cold chamber. The changes from set temperature were in the range of ±0.8°C and air velocity was low (0.23 ± 0.07 m/s). The surrounding surfaces were at the same temperature as the ambient air.

In *Study 1* six male subjects wearing insulated winter boots (W), 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 *Study 2* 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: a rubber boot (BS), a leather boot (AS) and an insulated leather boot for winter use (WS, a newer version of boot W that was used in *Study 1*). The boots BS were used at +2.8°C and − 11.8°C, WS at − 11.8°C and − 24.6°C and AS at all three temperature conditions. During the cold exposure the subjects mainly stood or sat (metabolic rate 80–100 W/m^2). Between 20^{th} and 30^{th} minute of cold exposure they walked on a treadmill at a speed of 5 km/h (metabolic rate around 160 W/m^2).

In both studies the subjects stayed in the cold for 1 hour. In addition, 20 minutes of recovery at room temperature was recorded for comparison. Foot skin temperatures were measured at 3 sites on both feet: lateral heel, dorsal foot and second toe. The average dorsal foot skin temperatures of all subjects from each trial were used for comparison of measured and predicted values. The measured shoulder skin temperature was used to estimate the mean skin temperature.

The measurement conditions of the tests on subjects are described in more detail in respective papers: *Study 1*-(Kuklane et al., 1999) and *Study 2*-(Kuklane et al., 1998).

Lotens' foot model

Lotens' model accounts for skin blood flow that depends on temperature, changes considerably and is the most important factor for 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.

Table 1 Insulation of the uppers and soles and weight of used boots

Boots	Uppers (m^2°C/W)	Sole (m^2°C/W)	Weight (kg)
W	0.332	0.311	0.83
AS	0.240	0.300	0.75
BS	0.219	0.246	1.01
WS	0.342	0.355	0.79

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 the 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.

Results

Large individual differences were present in foot skin temperatures. The dorsal foot skin temperature of different subjects could deviate from the mean for ±2.6°C (boot BS at − 11.8°C). In other measured locations the differences could be bigger, for example, in toes up to 13°C

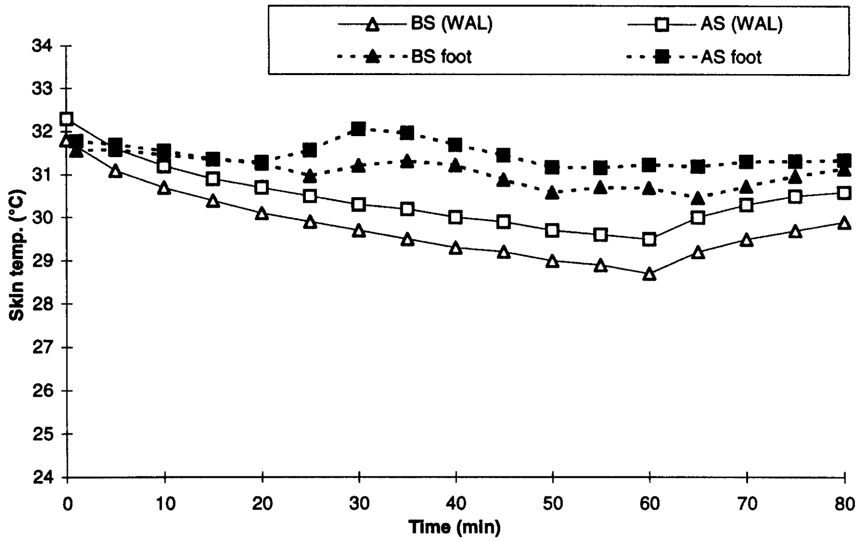

Fig. 1 Calculated (BS (WAL) and AS (WAL)) and measured (BS foot and AS foot) foot skin temperatures at environmental temperature of +2.8°C.

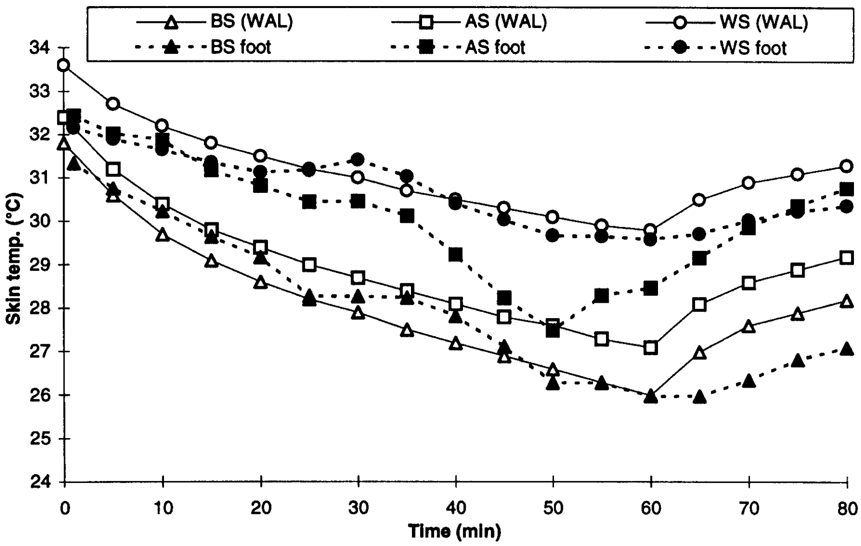

Fig. 2 Calculated (BS (WAL), AS (WAL) and WS (WAL)) and measured (BS foot, AS foot and WS foot) foot skin temperatures at environmental temperature of − 11.8°C.

between the subjects with the highest and lowest skin temperatures. At higher temperatures and/or with warmer footwear the differences were less.

Figures 1–3 show predicted and measured average dorsal foot skin temperatures for *Study 2*. The calculated values differed most at higher environmental temperature (+2.8°C) and the correlation was lowest there: for AS r=0.41, and for BS r=0.83. At lower temperatures the correlation was higher: r was between 0.88 (WS) and 0.93 (AS) for various boots and that can be considered a good estimate. In *Study 2* for all boots in all conditions r was 0.85 and for 2 colder conditions only it was 0.87. Figure 4 shows the predicted and measured temperature curves for *Study 1*. In this study the r was 0.95. 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. However, the *t*-tests showed significant differences between measured and predicted values, except for BS at − 11.8°C, WS at − 24.6 and for all measured conditions

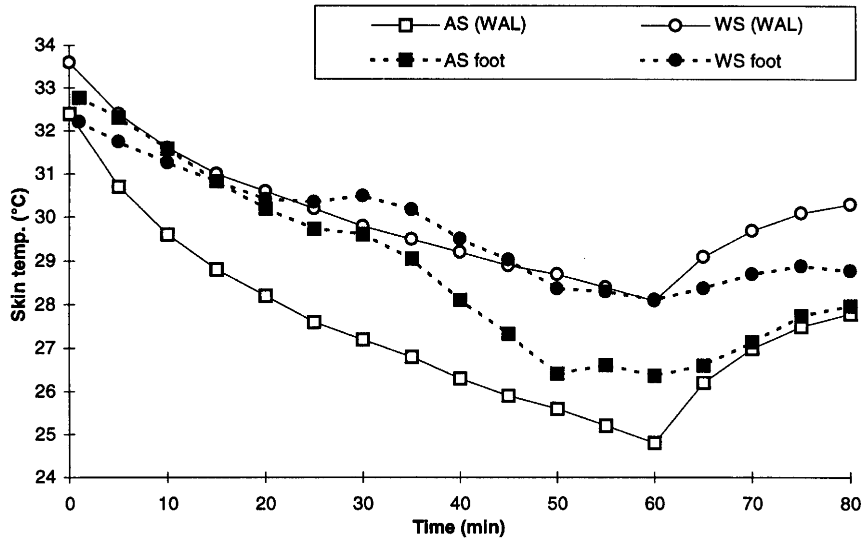

Fig. 3 Calculated (AS (WAL) and WS (WAL)) and measured (AS foot and WS foot) foot skin temperatures at environmental temperature of − 24.6°C.

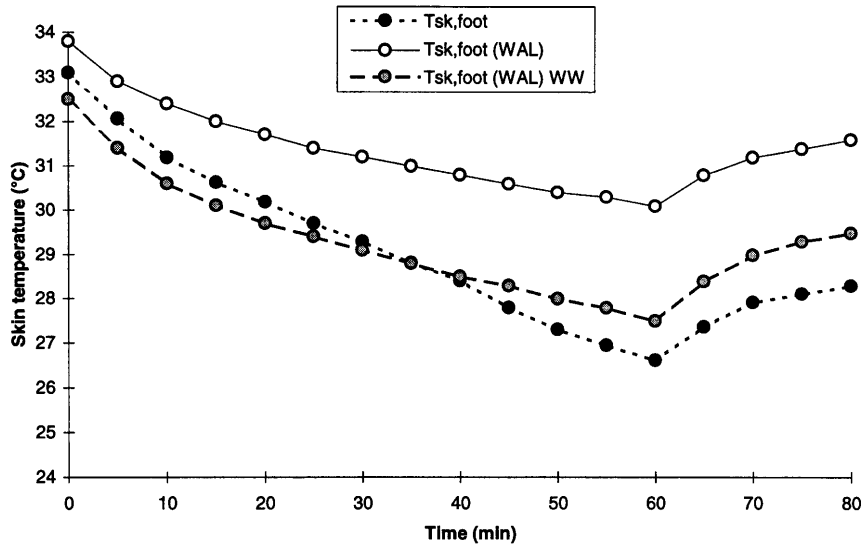

Fig. 4 Calculated ($T_{sk,foot}$ (WAL)) and measured ($T_{sk,foot}$) foot skin temperatures at environmental temperature of − 10.7°C (*Study 1*). $T_{sk,foot}$ (WAL) WW is calculated with estimated insulation reduction for sweating and walking.

together (including *Study 1*). Figure 5 shows the regression between measured and calculated foot skin temperatures for both studies.

Discussion

In *Study 2* 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.

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 (Table 1). Even the boot with lowest insulation (BS) had higher insulation while measured with thermal foot model. Lotens probably estimated his insulation values from Santee and Endrusick (Santee & Endrusick, 1988),

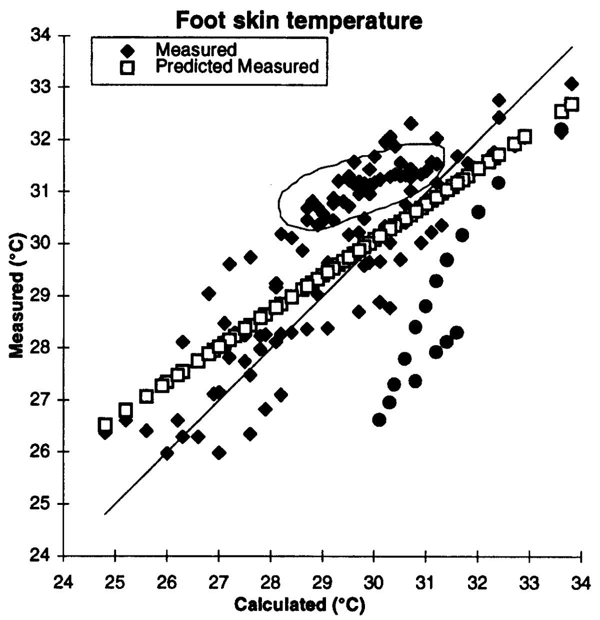

Fig. 5 Regression of measured versus calculated foot skin temperatures for both studies (r=0.71). • - values from *Study 1*; in marked area lay mostly the values from warmest exposure (+2.8°C) of Study 2; — - line of identity; "Predicted Measured" show the actual regression points between measured and calculated values.

reducing the values for wetting and motion. Similar reduction of the insulation of the uppers due to sweating and walking was observed by Kuklane and Holmér (Kuklane & Holmér, 1997), but that study showed that the insulation of the sole does not reduce during walking. However, during one hour exposure in the cold with relatively low activity the subjects did not have such a big sweat rate and insulation reduction due to it could be just minimal.

The underestimated insulation values used in the model development by Lotens can be the main reason why in *Study 1* (constant low activity) the predicted temperature stayed higher for the whole exposure period, using the high measured insulation values. In reality, the insulation of the boots was presumably at the same level for *Study 1* and in the tests during the development of the prediction model (Lotens, 1989; Lotens et al., 1989b). 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 Kuklane and Holmér (Kuklane & Holmér, 1997) (for uppers 45%, none for sole) then the paired *t*-test did not show significant differences any more (Fig. 4), while r=96. This was a similar correlation that Lotens got during the validation tests (Lotens, 1989; Lotens et al., 1989b). It shows that the curve patterns are similar (Fig. 4) and the main calculation corresponds to measured values, and only some parameter values differ.

The initial raise in foot skin temperature after cold exposure was usually quicker in Lotens model than in measured conditions (see *Study 2*, Figs. 1–3). During measurements the skin temperature kept on dropping more some minutes after leaving the cold room. The following foot temperature rise is often parallel in both measured and calculated data. This is more true for thin boots (AS, BS). In winter boots (WS) the foot temperatures of subjects rose more slowly than calculated values. During cold exposure in *Study 2* the measured values were often higher than predicted, but during recovery period the quicker rise of predicted temperature brought it to the same or even higher level than measured. This could be related to a higher time constant (thermal inertia) for warmer boots than present in the model.

It can be concluded that in *Study 1* the main reason for differences between measured and predicted foot skin temperatures were the differences in the estimation of the insulation values. In *Study 2* the differences were also caused by intermittent activity. At the two colder conditions in *Study 2* 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, 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.

Dry footwear insulation measured on a thermal foot model did not fit in Lotens' prediction model. However, when the dry insulation was reduced for sweating and walking then it could give reasonable foot skin temperature values. Regarding dry insulation values the Lotens' model needs a revision. It could be useful to improve and develop the model further in regards of intermittent activity and footwear insulation change. As foot temperature is related to whole body thermal state, then it should be possible to incorporate Lotens' calculation into a whole body model, e.g. IREQ. It could then get the input values for the calculation (T_{core} etc.) directly from the model calculations that are based on activity, insulation and environment.

Conclusions

- It is possible to use the insulation values from thermal foot measurements in the model calculations. If the limitations of the Lotens' foot model are considered, then it can give reasonable foot skin temperature values.
- The temperature recovery in tests with subjects usually starts somewhat later and is slower than calculated by Lotens' model.

- Foot skin temperatures during intermittent activity levels cannot be predicted with the present model.
- Lotens' foot model is a good base and it should be modified to take into consideration intermittent activity at various loads and insulation changes due to the moisture concentration and motion.

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