A COMPARISON OF LOTENS' FOOT MODEL AND DATA FROM SUBJECTS: THE USE OF BOOT INSULATION MEASURED WITH THERMAL FOOT MODEL IN CALCULATIONS

K. Kuklane[1], I. Holmér[1] and G. Havenith[2]

National Institute for Working Life, Dept. of Occupational Health, Solna, Sweden

[2]Loughborough University, Dept. Human Sciences, Loughborough, UK

INTRODUCTION

Local cooling of extremities is often the limiting factor during cold exposure. Lotens (1,2) has presented a model for prediction of foot temperature. The model includes factors such as blood flow to feet, body temperature and environmental climatic conditions. It is available as a computer program. Among the input parameters are the thermal insulation of the uppers and the sole of the footwear.

The purpose of this study was to validate predictions with the model using actual measurements on subjects exposed to cold environments. Values for footwear insulation were obtained from measurements with a thermal foot model.

METHODS

The footwear insulation was measured on a thermal foot model **(3).** The same type of sock that the subjects used was donned on the thermal model during the tests. The insulation value for uppers was 0.332 $m^2 \cdot °C \cdot W^{-1}$ and for soles 0.311 $m^2 \cdot °C \cdot W^{-1}$, and the weight of the boots was 0.83 kg.

The measurement conditions of the tests on subjects are described in detail elsewhere (3). In the study, *6* male subjects wearing the boots mentioned above, 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 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 temperature of all subjects from each trial was used for comparison of measured and predicted values. The shoulder skin temperature was measured as an indicator of overall body skin temperature.

Some of the 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 m2; area of sole, 0.021 m^2; rectal temperature, 37°C; and mean body skin temperature, 33°C. The default values were used for the remainder of the input data (1). The regression analysis and paired t-tests were used to acquire correlation coefficients and for statistics.

RESULTS AND DISCUSSION

For skin temperature calculation, the Lotens' foot model uses the nutritional blood flow that stays relatively constant and the skin blood flow that depends on temperature. The latter changes being the most important factor for the skin temperature change.

Figure 1 shows the predicted and measured temperature curves. The correlation coefficient between predicted and measured values was ***0.95.*** Measured and predicted foot skin temperatures were significantly correlated. However, the t-tests showed significant differences between measured and predicted values.

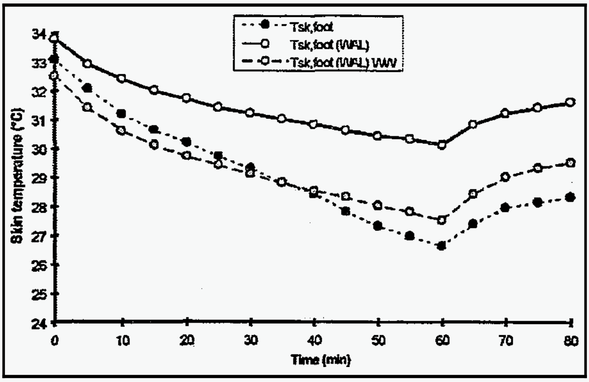

Figure 1. Calculated ($T_{sk,foot}$ (WAL)) and measured ($T_{sk,foot}$) foot **skin** temperatures at environmental temperature of -10.7°C. $T_{sk,foot}$ (WAL) WW is calculated with estimated insulation reduction for sweating and **walking.**

A 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) $m^2 \cdot °C \cdot W^{-1}$ (1), while the values measured with the thermal foot for a similar boot were much higher. Lotens probably estimated his insulation values from Santee and Endrusick (4), reducing the values for wetting and motion. Similar reduction of the insulation of the uppers due to sweating, and sweating and walking, was observed by Kuklane and Holmér **(5,6).** They showed that the insulation of the sole does not decrease during walking. However, during a 1h exposure in the cold with low activity, the subjects did not have a considerable sweat rate and the related reduction in insulation could be minimal.

The underestimated insulation values used in the model development by Lotens may be the main reason why the predicted temperature stayed higher for the whole exposure period using the high measured insulation values. In reality, the insulation of the boots stayed presumably at the same level. 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 **(6),** then the paired t-test did not show significant differences any more (Figure 1), while r = 96. **This** is a similar correlation that Lotens got during the validation tests (7). It shows that the curve patterns are **similar** and the main calculation corresponds to measured values, only some parameter values differ. Figure 2 shows the regres-

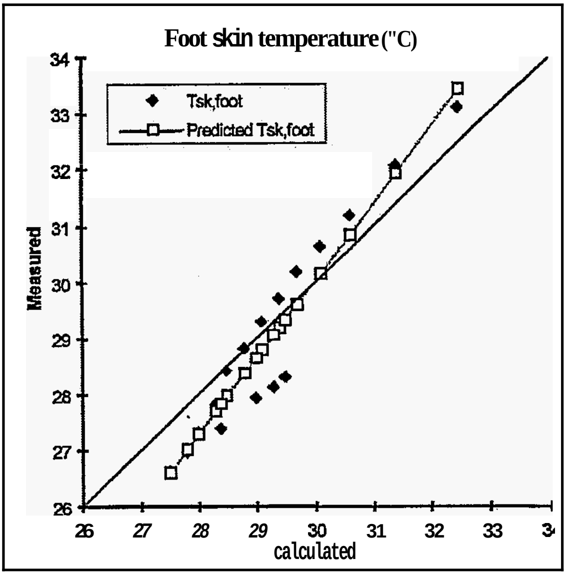

Figure 2. Regression of measured versus calculated foot skin temperatures (r = 0.96), after the insulation was corrected for sweating and walking. —— line of identity; "Predicted $T_{sk,foot}$" is the actual regression between measured and calculated values.

sion between measured and calculated foot skin temperatures after the correction of the insulation.

It can be concluded that the **main** reason for differences between measured and predicted foot **skin** temperatures is most likely the difference in the estimation of the insulation values.

When the average foot **skin** temperatures, based on all three measured points, were compared to Lotens' model, then the measured values were much lower due to considerably lower temperatures of toes and heels. It can be judged that the prediction model apparently does not consider cooling of local points, especially toes, which are usually critical for exposure length and/or comfort.

CONCLUSIONS

We conclude the following: Considering the disagreement in the insulation values, the Lotens' foot model gives reasonable prediction of foot skin temperature values. The use of insulation values from thermal foot measurements certainly improves the accuracy. The model should be modified to take into consideration insulation changes due to moisture concentration and motion.

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