Impact of local clothing values on local skin temperature simulation

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Abstract
Current human thermophysiological models calculate skin temperatures to predict human thermal comfort. To identify local influences on overall thermal comfort, local skin temperatures should be computed with high accuracy. This necessity depends on reliable input data of local clothing properties. However, only few data sets on local clothing insulation are published, and these values can be inconsistent. This paper analyses the effect of different sets of local clothing values on simulated skin temperatures using the thermophysiological model ThermoSEM. The skin temperatures are computed for a seated (1met), average man wearing a light clothing combination (0.5clo). Four sets of local clothing values are taken from the literature. This data is used to simulate local skin temperatures for uniform operative temperatures between 18°C and 34°C. Furthermore, the comparison to measured data is included. The results show that local skin temperatures are sensitive to the local clothing properties, and deviations might be up to 4K. These findings emphasize that local clothing parameters have to be chosen carefully. Additionally, current local clothing databases scarcely reflect the wide variety of clothing ensembles worn in practice. Therefore, this study underlines the need for further measurements of local clothing properties with detailed documentation of experimental set up.

Keywords: thermal modelling, local clothing, thermophysiology

1 Introduction
Current human thermophysiological models calculate skin temperatures in uniform and non-uniform environmental conditions to predict human thermal comfort. In non-uniform environments, local thermal dissatisfaction can negatively influence overall thermal comfort. To identify this effect, local skin temperatures should be calculated with high accuracy, which depends, among others, on reliable input data of local clothing properties. These properties include the clothing insulation or thermal resistance, the moisture permeability index or clothing evaporative resistance and the clothing area factors. These values are mostly published for whole-body applications in the literature. In case of local applications, only few studies are available concerning typical every day and office clothing ensembles. Moreover, the values can differ for the same prescribed outfit. The impact of these differences has not been analyzed in recent literature. To fill this gap, this paper gives an overview of recently published studies on local clothing properties and analyzes the impact of deviations in local clothing values on the prediction of local skin temperatures using the thermophysiological model ThermoSEM (Kingma, 2012).
2 Methods
This study compares the simulation outcome of different sets of clothing properties to each other and to one set of measured skin temperatures of a study case with four subjects. Therefore, this section will present the main simulation properties, the local clothing data sets, the environmental conditions of the study cases and the strategy of the data analysis.

2.1 Simulation model and general input data
All simulations in this study are done with the thermophysiological model ThermoSEM as described by Kingma (2012). This model uses 18 concentric cylinders and one concentric semi-sphere to characterize the human body (Figure 1). Every part has multiple tissue layers with defined attributes, e.g. basal metabolic heat, specific density and conductivity. Moreover, the elements are divided into anterior, posterior and inferior sectors, to account for differences due to the orientation. In the default model, these specifications represent an average adult man with a weight of 73.5 kg, a body surface area of 1.86 m² and a body fat percentage of 14%. Additionally, the basal metabolic heat production is set to 87.1 W. These values are not changed for the simulations in this study.

![Figure 1 Representation of the human body by the ThermoSEM model (Kingma, 2012)](image)

In addition to the basic input data, ThermoSEM requires the activity level, the data on the surrounding environment, and the properties of the worn clothing ensemble of the simulated person. In this paper, the activity level is set to 1 met, which represents a seated person performing light office activity (ANSI/ASHRAE, 2004). The low activity level is chosen, on one hand, to minimize influences on the local skin temperatures by heat production due to higher activity. On the other hand, it still provides the opportunity to compare the computed results to measurements in an office environment. The environment of the simulations is assumed to be uniform and steady state. To analyse the effect of different environmental temperatures on the results, five scenarios are designed with constant air and wall temperatures of 18°C, 22°C, 26°C, 30°C and 34°C. The relative humidity is kept constant at 40%. In all cases, the simulation time is 90 minutes, allowing the simulation to also reach steady state. The five environmental temperature scenarios are each combined with all clothing data sets representing a light clothing combination (overall insulation of 0.5 clo), which are described in detail in section 2.2.

2.2 Local clothing properties
In ThermoSEM and other multi-segment thermophysiological models, clothing properties have to be defined at every body part. These local clothing parameters usually include values for the local clothing insulation, the local moisture permeability and the local clothing...
area factor. For this study a clothing combination consisting of underwear, t-shirt, trousers, socks and shoes is chosen, because the highest number of data sets were available in this case. The clothing properties used in the simulation are obtained from the papers by Curlee (2004) and Nelsen et al. (2005), Havenith et al. (2012), Lee et al. (2013) as well as Lu et al. (2015), which are referred to as “Curlee”, “Havenith”, “Lee” and “Lu” as scenario names. All local clothing properties are summarized in Table 1.

The data by Curlee (2004) and Nelsen et al. (2005) are based on the whole-body data published by McCullough (1985, 1989), and then recalculated into local values. Hence, these papers provide local clothing insulation, evaporative resistance and area factor values for a variety of clothing items, which then can be combined into clothing ensembles. However, in contrast to whole-body values, the calculation of multi-layer clothing is not investigated. Therefore, two assumptions have to be made in case of multiple layers of clothing: 1) the clothing insulation values of separate clothing items are added up and 2) the largest values of the area factor and moisture permeability index is close to the combined value. The specific clothing items used in this study are listed in the second column of Table 1. Since the other studies do not provide local clothing area factors, the ones mentioned in Curlee (2004) and Nelsen et al. (2005) are adopted in the other scenarios (third column in Table 1).

<table>
<thead>
<tr>
<th>Body part</th>
<th>Clothing items</th>
<th>Local area factor**</th>
<th>Local clothing insulation (clo)</th>
<th>Moisture permeability index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Curlee (18-34°C)</td>
<td>Havenith</td>
</tr>
<tr>
<td>Whole body</td>
<td>--</td>
<td>--</td>
<td>0.57*</td>
<td>0.52</td>
</tr>
<tr>
<td>Head/Neck</td>
<td>None</td>
<td>--</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Chest</td>
<td>Bra, t-shirt</td>
<td>1.22</td>
<td>1.12</td>
<td>1.04 - 0.43</td>
</tr>
<tr>
<td>Back</td>
<td></td>
<td>1.22</td>
<td>1.12</td>
<td>1.04 - 0.43</td>
</tr>
<tr>
<td>Abdomen/Pelvis</td>
<td>Panty + t-shirt + trousers</td>
<td>1.17</td>
<td>2.07</td>
<td>1.04 - 0.43</td>
</tr>
<tr>
<td>Upper arm</td>
<td>T-shirt</td>
<td>(1.23)</td>
<td>0.75</td>
<td>1.04 - 0.43</td>
</tr>
<tr>
<td>Lower arm</td>
<td>None</td>
<td></td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Hand</td>
<td>None</td>
<td>--</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Thigh</td>
<td>Trousers (fitted)</td>
<td>1.20</td>
<td>0.93</td>
<td>0.97 - 0.67</td>
</tr>
<tr>
<td>Lower leg</td>
<td>Trousers (loose)</td>
<td>1.44</td>
<td>1.27</td>
<td>0.97 - 0.67##</td>
</tr>
<tr>
<td>Foot</td>
<td>Socks + shoes</td>
<td>1.25</td>
<td>1.85</td>
<td>0.61 - 0.34</td>
</tr>
</tbody>
</table>

* Men’s Summer Casual from (McCullough et al., 1989)
** taken from (Curlee, 2004; Nelson et al., 2005)
*** for the simulations a value of 0.82 is assumed
# assumed to be zero, since the ensemble is known (values corresponding to long-sleeved shirts are calculated otherwise)
## assumed to be same as thighs, since long trousers are set (values corresponding to shorts are calculated otherwise)
In Havenith et al. (2012), the local clothing insulation values are given as a function of the environmental temperature based on clothing typically worn in these conditions. Because of this method, also a clothing insulation at the lower arm is computed in environmental temperatures below 28°C. These values are set to zero, since this study prescribes a t-shirt for upper body clothing. Similarly, the clothing insulation values for the lower leg are very low in warmer conditions (representing shorts). This issue is solved by assigning the value of the upper leg also to the lower leg. Keeping these assumptions in mind, Table 1 presents the values at 18°C and 34°C operative temperature.

The local clothing insulation values in Lee et al. (2013) and Lu et al. (2015) are derived from measurements on a thermal manikin. Lee et al. (2013) provide these values for a large variety of typical office and outdoor clothing ensembles. In this study, the 8th outfit was chosen. A smaller number of clothing combinations are measured in Lu et al. (2015). For the analysis in this paper, the outfit with the case number EN9 is used. Unfortunately, no values for the head and the feet are available. To maintain a complete data set, the value for the foot insulation is taken from Lee et al. (2013).

Havenith et al. (2012), Lee et al. (2013) and Lu et al. (2015) do not calculate or measure values for the moisture permeability index. According to Havenith et al. (2012) and EN-ISO 9920 (ISO, 2009), a value of 0.34 is chosen for all clothed body parts.

2.3 Measured data

The measurements were done in the climate chambers by the department of the Built Environment, Eindhoven, The Netherlands and are part of comfort study investigating cooling strategies in office spaces. The subjects were seated at an office desk performing light activities (1 met). For this study, four male subjects were electable, since they wore a light clothing combination (0.5 clo) and their body composition (Table 2) was not too different from the default values of ThermoSEM.

<table>
<thead>
<tr>
<th>Table 2 Subject characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Male 1</td>
</tr>
<tr>
<td>Body mass [kg]</td>
</tr>
<tr>
<td>70</td>
</tr>
<tr>
<td>Height [m]</td>
</tr>
<tr>
<td>1.60</td>
</tr>
</tbody>
</table>

The experiments were performed in uniform conditions with a set point air temperature of 28°C. The actual air temperature and humidity were recorded during all experiments. Moreover, the skin temperature of the human subjects was measured at the 14 sites as suggested in ISO (2004) using iButtons (Thermochrom iButton DS1922L, Maxim Integrated, USA). Each experiment had a duration of 90 minutes.

For the comparison between measured and simulated data, the measured skin temperatures were averaged for the human subjects, and the standard deviation was calculated. Furthermore, simulations based on the measured environmental conditions are performed for each clothing combination of section 2.2. The comparison is then done for the last 45 minutes of the measured and simulated data allowing time for steady state conditions during the experiments.
2.4 Data analysis
In this paper, the results for the mean skin temperature and four local body sites are presented. Both the simulated and measured mean skin temperature is the average over the 14 local skin temperatures as suggested in EN-ISO 9886 (ISO, 2004). For representing local body parts, the skin temperatures of the upper arm, lower back, hand and foot were chosen.

For better comparison of the simulated scenarios with each other, the mean and local skin temperatures for each set of clothing data was averaged over the last 45 minutes. These calculations result in four comparable temperatures for each body part in every environmental temperature. For further analysis, the average and maximum difference is computed out of the four values for every body part at each operative temperature. For this, firstly, each difference in skin temperature is calculated per pair (Curlee/ Havenith, Curlee/ Lee, Curlee/Lu, Havenith/ Lee, Havenith/ Lu, Lee/ Lu) separately and then, the average and maximum is taken from these six values. The same is done for comparing the local clothing data.

3 Results
In this section the simulated skin temperature for the cases described in the previous section are compared. Firstly, this comparison is done within the four clothing scenarios. Secondly, measurements are compared to the simulated outcomes in the measured conditions.

3.1 Comparison of computed skin temperature in between simulation scenarios
The simulated mean and four local skin temperatures for all four sets of clothing values are compared for two environmental temperatures in Figure 2. The graphs show that differences in skin temperature between the four clothing data sets exist and that these deviations vary for different body parts as well as different environmental temperatures. For both illustrated uniform environmental temperatures of 22°C and 30°C, the highest deviations are found for the foot with a maximum difference in skin temperature of 4.5 K and 1.2 K, respectively. Furthermore, temperature differences also occur at non-clothed body parts, e.g. hands. Additionally, when comparing the order of the computed skin temperature from highest to lowest, it is notable that this order might change for different operative temperatures. For example, sorting the clothing data sets for the upper arm skin temperature from highest to lowest leads to Curlee > Havenith > Lee > Lu for an environmental temperature of 22°C and to Lee > Curlee > Havenith > Lu for an environmental temperature of 30°C.

To further investigate the variation of the computed skin temperature over different environmental temperatures, Figure 3 presents the maximum and average skin temperature difference (ΔT_max and ΔT_avg, respectively) of the mean and the four body parts for five uniform environmental temperatures. In the graph, two patterns can be found: 1) for upper arm and hand, ΔT_max and ΔT_avg drop with increasing operative temperature, and 2) for mean, lower back and foot, ΔT_max and ΔT_avg have a maximum at around 22°C and then decrease. Again, the highest deviations in skin temperature are found for the foot ranging from 0.8 K up to 4.5 K.
The relation between the differences in skin temperature and in clothing insulation is examined with the help of Table 3. The most striking observation is that even though no insulation is provided at the hand, the skin temperature can differ up to 1.1 K. Furthermore, the differences in clothing insulation of the foot and the lower back are very similar, but the skin temperature deviation is higher for the foot. Comparing the upper arm and lower back, the situation is switched. In this case, the differences in skin temperature are similar and the difference in clothing insulation of the lower back is higher. All in all, these observations indicate that the skin temperature of the body parts do not only depend on the clothing values provided for itself, but also on the clothing values of the other body parts.
### Table 3 Average and maximum differences in temperature and clothing insulation for two uniform environmental temperatures

<table>
<thead>
<tr>
<th>Body part</th>
<th>Operative temperature</th>
<th>Upper arm</th>
<th>Lower back</th>
<th>Hand</th>
<th>Foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average difference in skin temperature [°C]</td>
<td>22</td>
<td>0.7</td>
<td>0.8</td>
<td>0.6</td>
<td>2.4</td>
</tr>
<tr>
<td>Maximum difference in skin temperature [°C]</td>
<td>22</td>
<td>1.3</td>
<td>1.5</td>
<td>1.1</td>
<td>4.5</td>
</tr>
<tr>
<td>Average difference in clothing insulation [clo]</td>
<td>22</td>
<td>0.2</td>
<td>0.7</td>
<td>0</td>
<td>0.7</td>
</tr>
<tr>
<td>Maximum difference in clothing insulation [clo]</td>
<td>22</td>
<td>0.3</td>
<td>1.3</td>
<td>0</td>
<td>1.3</td>
</tr>
</tbody>
</table>

#### 3.2 Comparison of simulated and measured skin temperatures

For the comparison of simulated and measured skin temperatures, this paper uses the measured data set as described in section 2.3. The measured environmental data is used in all simulations as input data for the environment. In this case, the environmental temperature was uniformly around 28 °C. Figure 4 shows the simulated skin temperatures of all four clothing sets, the measured skin temperature averaged for all human subjects, and the standard deviation of the measurements. Again, graphs are presented for the mean and four body parts. It must be noted that the standard deviations of the measurements differ largely for the five shown graphs between ≈0.2 K (mean) and ≈1.2 K (upper arm). However, in this case this does not interfere with the main outcomes. For the skin temperature of the mean, upper arm, lower back and hand, most results are close to the averaged measured skin temperatures and fall within the standard deviation of the measurements. Also, the skin temperature deviations within the simulated results are smaller than 1 K as can be expected from the results in the previous section. However, larger differences are found for the foot skin temperature. In this case, all simulated results are below the measured ones and differ up to 2.5 K. Moreover, the deviation in skin temperature in between the simulations is also up to 1.8 K. The highest foot skin temperature (Curlee) corresponds with the largest clothing insulation value at the foot (Table 1). This finding suggests that the insulation values of the feet might need to be revised.
Figure 4 Comparison of measured and simulated results at an environmental temperature of ~28°C for the last 45 minutes of the measurements and simulations.

4 Discussion

The aim of the study was to identify the impact of variations in local clothing properties on simulated local skin temperatures. To achieve this goal, the recent literature was searched for data on local clothing properties. All in all, four studies were found providing data on office clothing options. However, to include the data of all four papers in this study, the clothing ensemble had to be limited to the light clothing ensemble as described in the methods (section 2.2). Moreover, three out of four studies only provided information on the local clothing insulation. The values for the local moisture permeability index and local area factor had to be assumed using standards or the fourth paper. However, the influence of the moisture permeability index was probably small, since sweating was limited in most cases due to low activity and moderate temperatures. Another issue of obtaining comparable data is that for measured values the conditions of measurements are not always stated clearly. Hence, differences in local clothing properties might be also due to this uncertainty. In summary, this study identifies a need for traceable and complete data sets for local clothing properties for a variety of office clothing ensembles.
The results of this study show that the simulation of local skin temperatures is influenced by the local clothing properties used for describing a specific clothing ensemble. The magnitude of this effect, however, can vary largely for different body sites and different environmental conditions. In this study, variations from 0.3 K up to 4.5 K were found. The highest values for all skin sites were reached at environmental temperatures of 18°C and 22°C. In lower environmental temperatures, the heat losses to the environment contribute a higher amount to the local and overall energy balances of the human than in warmer conditions. Therefore, variations in heat losses due to the differences in clothing resistance, might also be higher in colder conditions. This possibility might be overlapped by the fact that vasoconstriction is likely to occur at lower environmental temperatures. This effect limits the amount of heat contributed by the blood flow and hence, the variation in heat loss is more visible in the skin temperature calculation. This explanation might also clarify why the deviation in foot skin temperature exceeds the other body parts. At distal locations the blood flow is generally lower than for proximal body sites and vasoconstriction is more likely to occur.

The data analysis also identified that local clothing values not only influence the skin temperature of the applied body part, but also at other body locations. This effect can be seen in unclothed body parts and clothed ones. The reason most likely lies in the internal heat exchange via blood flows of each body part with the central blood pool. In the thermophysiological model used, the heat fluxes of the blood flows coming from each body part are mixed, and the resulting temperature is used for the returning blood flows in the next simulation step. Additionally, these values are corrected in some body parts, where counter current heat exchange occurs due to the close location of arteries and veins. In any case, this fact emphasizes the importance for accurate local clothing input values at each body location.

The comparison to measurements revealed that for some body parts, all simulated skin temperatures are located within the error of measurement. However, at other body parts (here foot), some or all simulations can under- or overestimate the measured skin temperature. In the present case, the foot skin temperature was underestimated by all simulations. However, the values of the temperatures do relate to the amount of clothing insulation as presented in Table 1. Therefore, a possibility is that the local clothing insulation at the foot is generally too low in the presented papers. Other causes might be the discussed dependence of one body part on all local clothing values or the thermal history of the human subjects.

In all presented and discussed cases of this paper, the environmental conditions were kept uniform and steady state. This was done to focus on the effect of local clothing properties on local skin temperatures. However, in thermal comfort research the prediction of local skin temperatures and the resulting local sensation as well as local comfort votes are of special interest in non-uniform conditions, e.g. local heating of hands or face cooling. These situations could be included in future research to give a complete picture of the discussed issue in this paper.

The graphs comparing simulated and measured data also show that the thermophysiological model predicts the mean skin temperature fairly accurate, while larger deviations can be found at local skin sites. The skin temperature of these locations is included in the calculation of the mean. In the case of a 14-point mean, differences are reduced because over- and underestimated numbers cancel each other out and because of the amount of
points. In case of a lower number average calculation, the influence of each body part is larger, which might change the result. Therefore, this option has to be considered carefully. In addition, the discrepancy between mean and local skin temperatures are relevant when validating a thermophysiological model.

5 Conclusions
In this study, the impact of local clothing values on local skin temperature simulation is investigated. This analysis was done by comparing the simulation outcome of four sets of clothing properties representing one clothing ensemble to each other and to measured data. The main conclusions of this paper are that:

• only few studies are published providing local clothing properties for typical office clothing ensembles,
• variations in thermal and moisture resistance are found in these papers,
• different sets of local clothing properties affect computed local skin temperatures also for the uncovered body parts such as hands,
• the magnitude of the deviations depends on the environmental temperature and skin site.

For future research, this study underlines the need for further measurements of local clothing properties, which include clothing insulation, moisture permeability and area factor values, and contain a detailed documentation of the experimental set up.

Furthermore, the skin temperatures are typically translated into local thermal sensation or thermal comfort in thermal modelling. Therefore, the effect of the variation in skin temperature is very important for predicting (local) thermal comfort and needs to be investigated further in upcoming research.

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References