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Accuracy of mean skin temperature calculations and measurements in thermal comfort-related assessment

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ABSTRACT

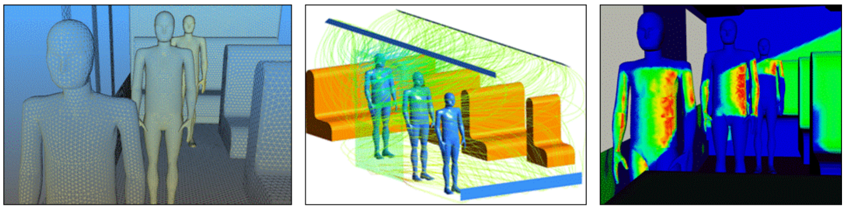
People inside spaces are subjected to different inhomogeneous indoor climate conditions like radiation, convection and conduction. Those environmental effects have to be considered in local and global thermal sensation and comfort models. Local models are formulated based on measured skin surface temperatures at different body parts. Global comfort prediction is based on calculated mean skin temperatures taken as input parameter. Thereby, the evaluation of weighted mean skin temperatures is a key parameter which is influenced by several effects. A wide variation of local skin temperatures influences area measurements, if such values are derived from single-point measurements. Additionally results may deviate significantly due to inadequate definitions and interpretations of individual body parts in literature. The paper analyses calculation methods with special focus on accuracy and uncertainty. The dispersion of values is demonstrated, quantified and recommendations are given for body segment definition with respect to measurement positions. Appropriate weighting functions are derived.

Keywords: thermal comfort, thermal sensation, inhomogeneous indoor climate, mean skin temperature, local skin surface temperatures

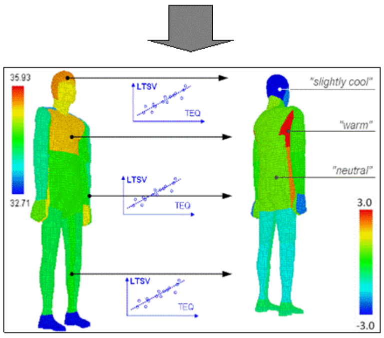
INTRODUCTION

Individuals are exposed to different indoor climate conditions and are subject to heat transfer by heat radiation, convection due to air flow and conduction through several clothing insulations. In several cases, thermal conditions are inhomogeneous and may further vary over time. All these heterogeneous environmental effects can be addressed by so-called Multi Physics simulation approaches. This makes it possible to consider global and local climatic effects which influence thermal sensation and comfort. For that purpose our research team developed and tested the middleware platform CoSimA+ (Co-Simulation Adaptation platform), which allows coupling different heterogeneous software tools for distributed numerical simulation (Stratbücker & van Treeck, 2010).

To estimate global and local thermal sensation and comfort of humans under different indoor climate conditions, meaningful physiological parameters are necessary. The most commonly used parameter as input for thermal comfort modeling is the skin surface temperature, which reflects the thermo-physiological reaction of the human body to the current ambient conditions (Figure 1).



Surface Model CFD Model IBP Radiation Solver



Resultant local skin temperatures and thermal sensation votes

Figure 1: Multi-physics simulation of different inhomogeneous environmental effects inside spaces, here in terms of a passenger cabin model, and resultant local surface temperatures of the human skin to estimate local thermal sensation votes (LTSV); bottom figure adapted from (van Treeck et al. 2009).

Local thermal sensation and comfort models are mostly formulated based on regressions taking measured skin surface temperatures at different body segments as input. The global part in comfort modeling is predicted from calculated mean skin temperatures. Thereby, the evaluation of weighted mean surface temperatures of the human skin is influenced by several thermal effects.

Several different equations have been proposed in the literature taking variable numbers of body parts and body locations as a basis for mean skin temperature evaluation (Burton, 1935; Crawshaw et al., 1975; Hardy & DuBois 1938; ISO 9886, 1992; Kurata & Funazu, 1954; Lund & Gisolfi, 1974; Mitchell & Wyndham, 1969; Nadel et al., 1971; Nadel et al., 1973; Mochida, 1977; Mochida, 1983; Ouyang, 1985; Ramanathan, 1964; Teichner, 1958). Thus, weighting coefficients differ in type (area weighted, sensitivity weighted, etc.) and value.

Uniform definitions of such locations are missing with respect to the definition and interpretation of the selected body parts and their corresponding segment-wise local body locations such as anterior, posterior or inferior. Investigating the whole set of possible combinations of different body locations and body parts, we observe a wide range of evaluated mean skin temperature values.

In terms of thermal sensation and comfort estimation, exact and precise body locations have to be established in order to avoid significant prediction errors. This becomes important especially in the warmth-related comfort area as a result of the asymmetric human thermoregulatory system (Romanovsky, 2007, Zhang et al., 2010). This asymmetric behaviour is clarified by Figure 2. Using the virtual thermo-physiological human manikin model of Fiala (Fiala et al., 2001) skin temperature simulations are conducted taking thermal environmental conditions as input, which correspond to the whole range of Predicted Mean Vote (PMV) values of Fanger's model (Fanger, 1970; DIN EN ISO 7730, 2006).

It becomes apparent, that variations of the mean skin temperature in the warmth-related comfort area are highly sensitive within a fairly small temperature range of <1 K. A diminutive deviation of the mean skin temperature already causes a considerable shift towards warm discomfort (Zhang et al., 2010). (This is due to the fact, that thermal sensation is further influenced by skin wetness in the warmth-related area.) In contrast, a small change in skin temperature within the cool-to-cold comfort area has a comparably small effect within the temperature range of ≈5.4 K. We conclude that it is of key importance to define a unified calculation method in order to evaluate mean temperatures of the human skin at high precision.

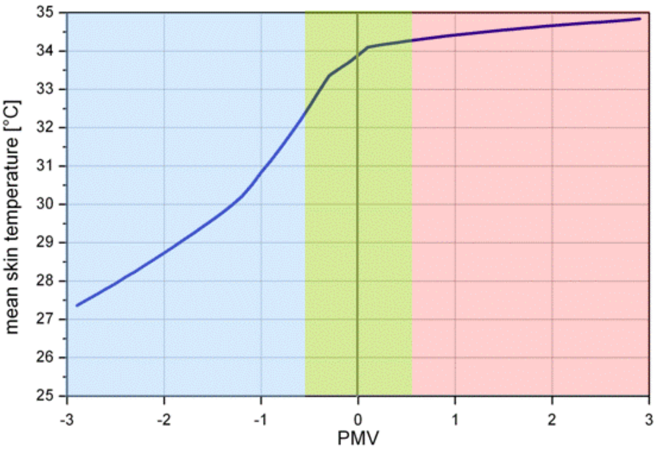


Figure 2: Mean skin temperature as a function of Predicted Mean Vote (PMV). The results are obtained from a thermo-physiological simulation using the virtual thermoregulation model Fiala-FE (Paulke, 2007) over the whole PMV range.

In the following, we compare varied numbers of formulas using one up to 22 body parts for the evaluation of the mean skin temperature. Additionally, their dispersion towards given reference temperatures resulting from the Fiala model are demonstrated and quantified. At the end, recommendations are given for body segment definition with respect to measurement location. Appropriate weighting functions are derived.

STATE OF THE ART

Comparisons of equations for the calculation of the mean skin temperature have been done since the 1930s (Choi et al., 1997). The aims for this are diverse, reaching from the use of the mean skin temperature as an index for physiological reactions of the human body towards different ambient conditions (Eichna et al., 1950; Teichner, 1958; Mochida, 1977; Nielsen & Nielsen, 1984; Liu et al., 2011), over completely new equation evaluations (Mochida, 1977; Mochida, 1983; Kuwabara et al., 2006), in terms of measurement expenditure reduction (Teichner, 1958) and improvement of measurement precision (Nielsen & Nielsen, 1984; Choi et al., 1997) up to thermal comfort prediction (Liu et al., 2011). All have in common that they use the formula with the highest number of local body parts as the most precise reference for the mean skin temperature in terms of comparison to the remaining equations. Up to now a various number of calculation methods have been developed and different approaches are proposed to define the most reliable equation to evaluate the mean skin temperature.

METHODOLOGY

Materials

In this study we use a finite element implementation of Fiala's thermoregulation model (Paulke, 2007). This model divides the human physiology into 19 cylindrical or spherical body segments (head, thorax, etc.) further subdivided into sectors (anterior, posterior, inferior) to account for asymmetric local ambient conditions. Altogether 48 sectors represent different body measurement locations in terms of mean skin temperature calculation. The simulation of Fiala-FE under pre-defined ambient conditions delivers 48 local skin temperatures to calculate corresponding mean skin temperatures.

Calculation of local skin temperatures using Fiala-FE

For evaluating different mean skin temperature equations, reliable local skin temperatures are required as input parameter. The Fiala model is used in combination with own software code to calculate mean radiant wall temperatures equal to the mean ambient air temperature, necessary for global thermal comfort prediction using the PMV index. Additionally applied parameters like activity index, workload, clothing insulation, relative air humidity and air velocity can be obtained from Table 1.

Table 1: Constant parameters for PMV calculation

Parameter	Value	Unit
Activity level	1.2	Met
workload	0	Met
clothing insulation	0.38	Clo
relative air humidity	40	%
air velocity	0.1	m/s

As a result of the simulation, steady state local skin surface temperatures are obtained from each of the 48 sectors to calculate corresponding mean skin temperatures by all extracted equations from literature.

For the calculation of the mean skin temperature references we consider two possibilities:

- Area weighted mean skin temperatures. Resulting local sector temperatures are multipied with their corresponding area factors. The sum of all the 48 area weighted temperatures yields the mean skin temperature.
- The second possibility is similar to the aforementioned one except for multiplying area weighted local skin temperatures with an additional sensitivity coefficient, expressing the thermal sensitivity of the local body sectors towards the ambient climate.

The two resulting mean skin temperatures are 33.9 °C for the area weighted temperature and 34.0 °C for the sensitivity weighted mean skin temperature.

Equations for mean skin temperature calculation

Various equations calculating the mean skin temperature by using up to 22 body parts have been extracted from literature. All these equations are containing different types of weighting factors and diverse combinations of body locations, which leads to a total number of 43 equations. Because of the poorly defined measurement sites, needed for the calculation of the mean skin temperature, some common equations appear more often but with varying combinations of body locations.

For example, Hardy & DuBois (1938) use 7 different body locations as measuring sites for the calculation of the mean skin temperature. Teichner (1958) bases his study on this equation and used forehead, chest, lower arm, palm, thigh, calf and sole as measuring sites. Mochida (1977) also uses the Hardy & DuBois (1938) equation, but his body locations differ from Teichner's version. His configuration contains forehead, abdomen, lower arm, hand back, thigh, tibia and instep. The apparent problem is the lack of the exact definition of the measuring sites concerning for example the lower arm and thigh. In case of our virtual manikin Fiala-FE it would be possible to take the temperature from 3 different measuring spots, which are lower arm anterior, lower arm posterior and lower arm inferior. The same procedure would be possible for the thigh. As a result, 9 additional variants to calculate the mean skin temperature appear.

Identification and interpretation of the local body locations of each selected equation in respect to the segmentation of the virtual manikin model causes multiple degrees of freedom. In this paper, all possible combinations of local body sectors concerning the different calculation equations, extracted from literature, are considered. This leads in total to an amount of 2385 variants.

Dispersion of mean skin temperatures

Due to the high amount of mean skin temperature calculation equations and the resultant scattering of mean skin temperatures as a consequence of inadequate measurement site definitions, it is necessary to find a criterion for the evaluation of calculation accuracy.

For this reason we define a temperature range reaching from 33.9 °C to 34.0 °C based on the reference mean skin temperatures resulting from a Fiala simulation for thermal neutrality (PMV=0). The results are depicted by box plots in which the reference temperature range is marked by a permanent coloured rectangle. The calculated mean skin temperatures have to intersect this rectangle to be accepted as appropriate. To identify the most accurate equation out of the 43 extracted equations for the calculation of the mean skin temperature, we firstly classify them by their amount of body parts. All equations using the same number of body parts are summed up and represented by a single box. Boxes not intersecting the rectangular range are eliminated and marked as inappropriate. As a result, the amount of equations reduces. The remaining equations are analysed in more detail according to their number of body parts and source of equation (Burton, 1935; Hardy & DuBois, 1938, etc.). Finally we obtain the most accurate equation to calculate the mean skin temperature.

RESULTS

Figure 3 summarizes a total amount of 2385 calculated mean skin temperatures. Temperatures are classified with respect to their number of body parts and represented in separate boxes.

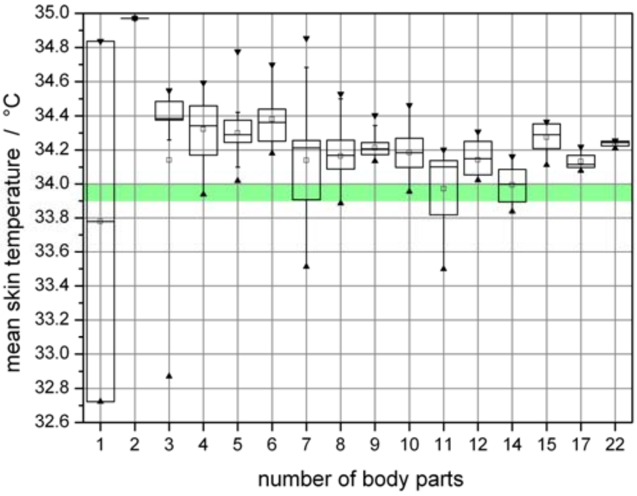


Figure 3: Derivation of calculated mean skin temperature equations using up to 22 body parts.

From Figure 3 it is apparent that there is at least one equation containing 1, 4, 7, 8, 10, 11 or 14 body parts, which intersects the thermal neutral area. Equations using 2, 3, 5, 6, 9, 12, 15, 17 and 22 body parts are over- or underestimating the mean skin temperature. This allows a pre-selection of appropriate calculation equations.

As the different boxes summarize all equations using the same number of body parts, it is necessary to obtain the special equation being responsible for the intersection between thermal neutral area and the box itself. This makes it necessary to separately analyse the different equations (Figure 4).

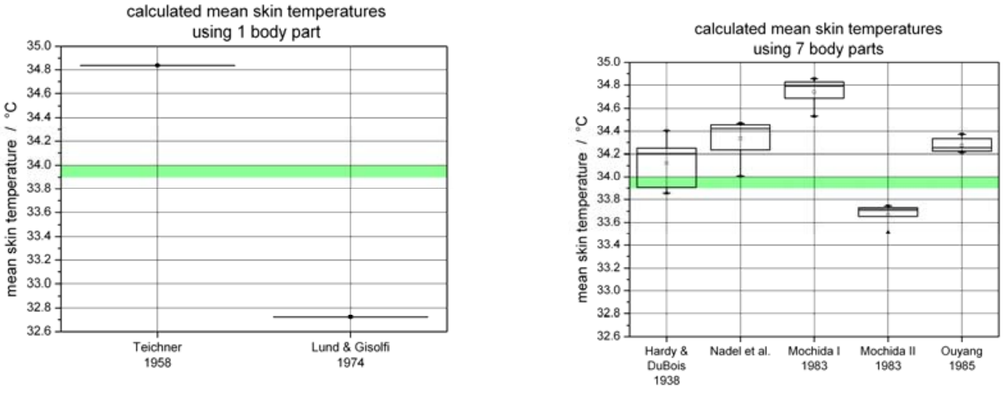


Figure 4: Analysis of equations after pre-selection according to the thermal neutral area (PMV=0).

The left graph of Figure 4 shows the mean skin temperatures calculated according to Teichner (1958) and Lund & Gisolfi (1974) using only a single body part as an example resulting from our study. Teichner´s equation clearly overestimates the defined reference temperature range by more than 0.8 K, whereas the equation according to Lund & Gisolfi underestimates this range by more than 1.1 K. Although the pre-selection suggests the calculation of the mean skin temperature by a single measurement point as accurate, it now becomes clear that neither Teichner´s nor Lund & Gisolfi´s equation are appropriate and have to be excluded. A similar behaviour could be obtained from the equations according to Ouyang (1985) and Kurata & Funazu (1954) using 11 body parts.

In our study none of the equations using 11 body parts holds the accuracy criterion. Thus they are not considered and are regarded as inappropriate.

The right picture of Figure 4 reveals the accuracy of Hardy & DuBois (1938) and Nadel et al. (1971). Both researchers used 7 body parts for the mean skin temperature calculation. As a result of the multiple calculation equations, it has to be remarked, that the calculation equation for Nadel et al. leading to an intersection of the calculated mean skin temperature and the reference temperature area, originates in his paper from 1971 and is used as Nadel et al. (1971). Additional researchers investigating inappropriate equations concerning 7 body parts are Mochida I (1983), which used a combination of relative area and heat transfer coefficients as weighting factors, Mochida II (1983) using relative area factors, heat transfer coefficients and sensitivity as weighting factors and Ouyang (1985) considering only area ratios.

In summary, eight out of the twenty pre-selected equations calculate the mean skin temperature equal to our defined temperature range.

Those equations are:

- Ramanathan (1964), using 4 body parts
- Hardy & DuBois (1938) and Nadel et al. (1971), using 7 body parts
- Crawshaw et al. (1975) and Nadel et al. (1973), using 8 body parts
- Teichner (1958) and Mitchell & Wyndham (1969), using 10 body parts
- ISO 9886 (1992), using 14 body parts

The resulting body part combinations can be extracted from Figure 5. Proper weighting factors are listed in Table 2.

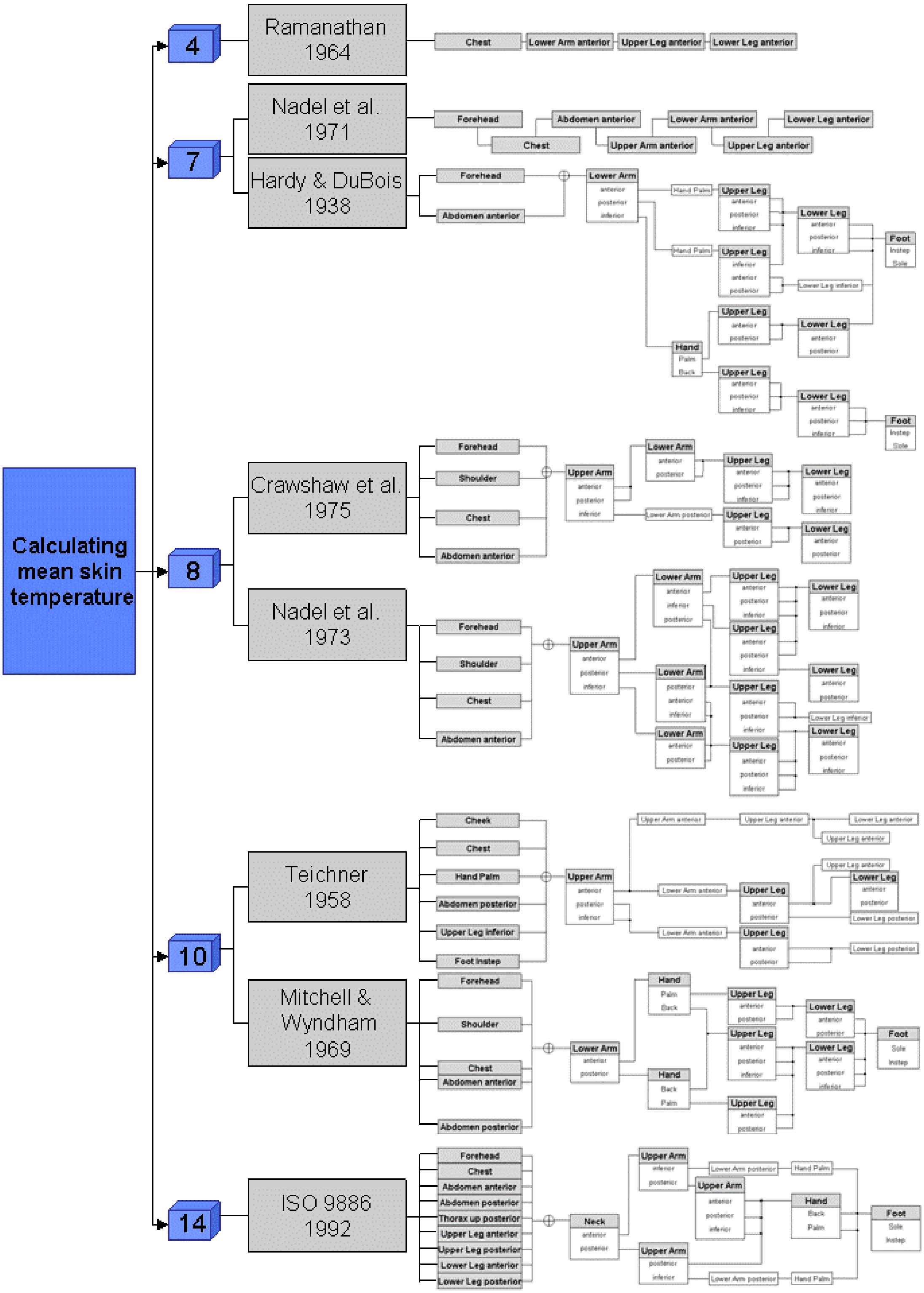


Figure 5: Recommended body part combinations for the calculation of mean skin temperatures. Equations are sorted by the number of local body parts used (4, 7, 8, 10 and 14) and show the resulting combinations.

Table 2: Weighting factors for mean skin temperature calculation equations. Selection of weighting factors depends strongly on the combination of body parts (see Figure 5).

Calculating method	Local segment	Weighting Factor	Local segment	Weighting Factor
Ramanathan (1964)	Chest	0.30	Low Arm ant.	0.30
	Up Leg ant.	0.20	Low Leg ant.	0.20
Nadel et al. (1971)	Forehead	0.07	Chest	0.18
	Abdomen ant.	0.18	Up Arm ant.	0.13
	Low arm ant.	0.12	Up Leg ant.	0.16
	Low Leg ant.	0.16		
Hardy & DuBois (1938)	Forehead	0.07	Abdomen ant.	0.35
	Low Arm	0.14	Hand	0.05
	Up Leg	0.19	Low Leg	0.13
	Foot	0.07		
Crawshaw et al. (1975)	Forehead	0.19	Shoulder	0.09
	Chest	0.08	Abdomen ant.	0.12
	Up Arm	0.13	Low Arm	0.12
	Up Leg	0.12	Low Leg	0.15
Nadel et al. (1973)	Forehead	0.07	Shoulder	0.09
	Chest	0.09	Abdomen ant.	0.18
	Up Arm	0.13	Low Arm	0.12
	Up Leg	0.16	Low Leg	0.16
Teichner (1958)	Cheek	0.10	Chest	0.10
	Hand Palm	0.10	Abdomen post.	0.10
	Up Arm	0.10	Up Arm / Low Arm	0.10
	Up Leg inf.	0.10	Up Leg	0.10
	Up Leg / Low Leg	0.10	Foot Instep	0.10
Mitchell & Wyndham (1969)	Forehead	0.070	Shoulder	0.088
	Chest	0.088	Abdomen ant.	0.088
	Abdomen post.	0.088	Low Arm	0.140
	Hand	0.050	Up Leg	0.190
	Low Leg	0.130	Foot	0.070
ISO 9886 (1992)	Forehead	0.071	Chest	0.071
	Neck	0.071	Abdomen ant.	0.071
	Abdomen post.	0.071	Thorax up post.	0.071
	Up Arm	0.071	Up Arm / Low Arm	0.071
	Hand	0.071	Up Leg ant.	0.071
	Up Leg post.	0.071	Low Leg ant.	0.071
	Low Leg post.	0.071	Foot	0.071

The weighting factors (Table 2) for each local body part strongly depend on the selected number of body parts and their combination (see Figure 5). In a first step, the amount of body parts has to be chosen according to the experimental setup. Afterwards the corresponding equations can be selected. This selection furthermore defines the possible combinations of the different body parts and affects the adjacent combination path (Figure 5).

Figure 6 exemplarily shows the classification of the calculation equations for the mean skin temperature using 7 body parts by the PMV index. It becomes evident that a false combination of body parts within the recommended equations or the use of equations which are classified as inappropriate, lead to a shift of the PMV index from thermal neutrality (PMV=0) to the uncomfortable zone (-0.5 > PMV > 0.5).

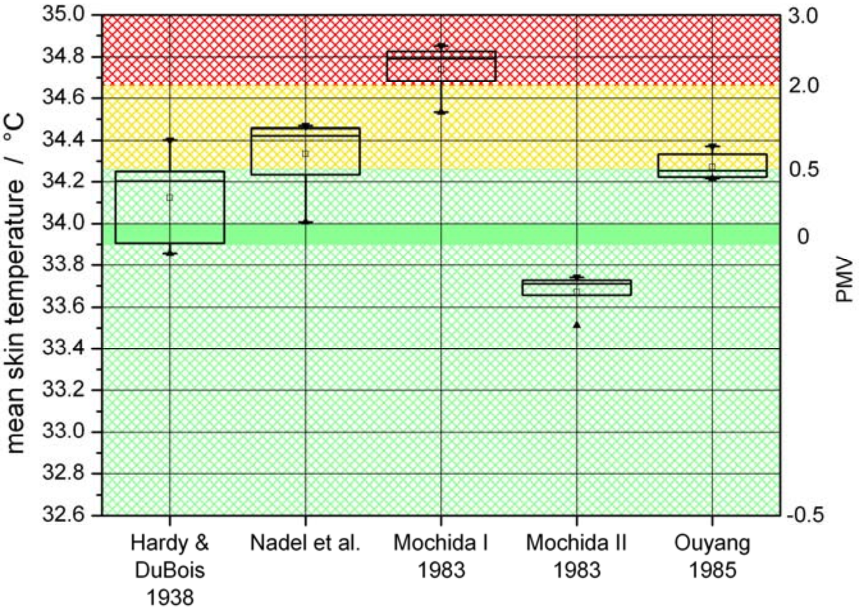


Figure 6: Calculation equations for mean skin temperature using 7 body parts and their classification by the PMV index.

DISCUSSION

The study shows the necessity for well-defined measurement locations in terms of mean skin temperature calculation for the improvement of thermal comfort prediction using the mean skin temperature as an important indicator for the thermoregulatory reaction of the human body. Accurate calculation results are required especially in the warmth-related comfort area, where small changes in mean skin temperature in the order of magnitude of 0.1 K already cause high impacts on the thermal comfort perception (Figure 2). As others conclude, the human thermoregulatory system offers a highly asymmetric behaviour (Romanovsky, 2007; Zhang et al., 2010). This originates from the facts that the cells of the human body consist of proteins which decompose at temperatures around 42 °C and the necessity of keeping a constant body core temperature of about 37 °C as the operating temperature for vital organs (Romanovsky, 2007). Hence, the human body is more sensitive towards heat stress than cold stress. This behaviour is reflected in the different mean skin temperatures resulting from the thermoregulatory actions of the human body under diverse ambient conditions and used as a meaningful parameter for predicting thermal comfort. The simulations shown in Figure 2 confirm this asymmetry for ambient conditions causing the corresponding mean skin temperatures for the whole PMV range.

Approaches exist, using thermographic pictures for calculating the reference mean skin temperature (Choi et al., 1997). This technique is able to generate some local temperature information resulting from each pixel and therefore depend on the resolution of the chosen measurement equipment (Choi et al., 1997). However, there are problems concerning the calibration of the measurement equipment in terms of emissivity coefficients of the surrounding surfaces and the human skin. The information loss evoked through covered body surfaces like head, clothed body parts or foot soles lead to additional calculation errors concerning the mean skin temperature.

The most common approach for the selection process of the appropriate mean skin temperature equation is based on the comparison between a predefined calculation equation using the highest number of body parts and a various number of other equations originating from literature. In this study, we use the Fiala-FE model for the definition of a reference mean skin temperature range, because it allows to split the human skin surface into as many virtual local measurement areas as required. The model itself shows good performance in predicting the human thermophysiological responses towards various dynamic and static ambient conditions (Foda et al., 2011).
In total, 43 equations with an amount of 2385 variants are investigated. As a result, 8 equations (Table 2) are able to predict the reference mean skin temperature according to the thermal comfort range (PMV=0) defined on the basis of the simulation results gained from the Fiala model. The combination of body parts concerning those 8 equations can be retrieved from Figure 5. It is really important to follow the recommended tree structure - otherwise the equations are over- or underestimating the corresponding mean skin temperature. The consequence is a fatal error in the prediction of thermal comfort as indicated in Figure 6.

CONCLUSIONS

In total we have analysed 2385 possible body part combinations resulting from 43 different equations for the calculation of the mean skin temperature. With respect to thermal comfort prediction we clarified the importance of exact definitions of body parts and showed their appropriate combinations concerning 8 remaining equations satisfying our criterion for thermal neutrality (PMV=0). Currently we are developing interfaces to other computational codes using our co-simulation adaptation platform CoSimA+ (Stratbücker & van Treeck, 2010) which allow the definition of realistic environmental scenarios. Thereby, the use of a virtual thermal manikin model can be a useful extension for the development of global and local thermal comfort models.

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