INDIVIDUALIZATION OF A MATHEMATICAL MANIKIN MODEL IN TERMS OF GENDER, AGE AND MORPHOLOGICAL ISSUES FOR PREDICTING THERMAL COMFORT: A PRELIMINARY STUDY

Daniel Wölki[1], Christoph van Treeck[1]
[1]RWTH -Aachen University, Chair in Energy Efficient and Sustainable Building (E3D), Aachen, Germany

ABSTRACT

To holistically understand the influence of inhomogeneous and dynamic indoor climatic effects on human thermal comfort, it is essential to investigate the appropriate dynamic human thermoregulatory processes and their complex interdependencies within the body. Although gender and age specific differences in thermal comfort perception are well known, the numerous mathematical model approaches proposed in literature, typically consider a standard human being of male gender. The research approach of this paper therefore focuses on the adaptation and parameterization of the physiological part of a virtual human thermoregulatory system to be able to represent different morphological groups of humans. The aim is to improve the model's prediction accuracy towards local and global indoor thermal comfort. In this regard, the use of detailed simulation models can support the invention of control strategies for energy saving and cost effective buildings, which is important to keep up with the turnaround in energy policy, while coping with today's constantly growing energy demands.

INTRODUCTION

For thermal comfort assessment in building design it is common practice to use statistical models to directly correlate ambient climate with thermal sensation (Fanger, 1970). The PMV/PPD model is regarded suitable for uniform morphologies/anthropometries and steady state conditions near thermal neutrality (Schellen, 2012). However, understanding the impact of inhomogeneous and time dependent indoor climatic effects on human beings lacks for a more detailed understanding of the dynamic human thermoregulatory processes and their complex intracorporeal dependencies. In this context numerous mathematical model approaches have been proposed in literature (Fiala et al. 1999, 2001; Huizenga et al., 2001; Stolwijk, 1971; Tanabe, 2002), which are generally based upon standardized anthropometrical and morphological data (male gender, body height of 1.76 m, a body weight of 73.5 kg, a muscle content of 42.21 % and a body fat content of 14.44 %). Only a few authors addressed the aspect of individualization so far (Kingma, 2012; Novieto, D.T., Zhang, Y., 2010; van Marken Lichtenbelt et al., 2007; Havenith, 2001).

Our research objective is the adaptation of the physiological part of a virtual human thermoregulatory system to different morphological groups of people. In a previous study we already identified so-called key parameters and investigated their impact on the virtual thermoregulatory system by means of sensitivity analysis (Wölki et al., 2011). This contribution deals with the differences in body fat content (BF) between males and females of different ages. Gender and age specific discrepancies in BF and body fat distribution are a matter of common knowledge (Durnin & Womersley, 1974; Davidson et al., 2011). Such differences might be of great importance in terms of local and global thermal comfort assessment (Huizenga et al., 2001). Because of the insulating characteristics, the body fat tissue plays an important role for the heat balance of the human body. Under cold climatic conditions such an additional insulation layer represents an advantage since it delays the heat losses from the body core to the environment. Regarding warm surroundings this insulation effect would quickly cause hyperthermia (Anderson, 1999), because of the highly asymmetric (body core temperature of about 37 °C) human thermoregulatory system (Romanovsky, 2007; Zhang et al., 2010). The activity of the human thermoregulatory system itself is reflected through varying skin and body core (hypothalamus) temperatures. Whereas local skin surface temperatures are commonly used as important input parameters for local thermal comfort models (Zhang et al., 2010), their cumulative value, the mean skin temperature, is applied to global thermal comfort prediction models (Streblow, 2010; Zhang et al., 2010).

SIMULATION AND EXPERIMENT

Materials

A FEM-implementation (Paulke, 2007) of Fiala's thermophysiology model (Fiala et al., 1999, 2001) serves as a base model for our investigations concerning the physiological part of the human thermoregulatory system. The virtual physiological part of the model is called the "Passive System" and approximates the human physiology by means of 19 cylindrical and spherical body segments (e.g. legs, arms, head, etc.). Each body segment consists of different virtual tissue layers, which contain specific characteristics like heat conductance, blood circulation, metabolic rate, heat capacity, tissue density, length and diameter. The tissue layers are hierarchically structured and start with bone as the center element followed by muscle, fat and skin. The skin itself represents the interface between the virtual human and its ambient climate. In addition to the physiological tissue layers, segmental clothing layers can be applied. Their local thermal resistance values are listed in Paulke (2007). To account for local and asymmetric ambient conditions, the different body segments can be further subdivided into body sectors, leading to a total amount of 48 sectors. The heat balance of the virtual human body is directly influenced by active temperature regulation mechanisms like sweating, shivering, vasoconstriction and vasodilatation. It is sourced out into the so-called "Active System". Both, the "Active System" and the "Passive System" can be interconnected to represent the whole virtual human thermoregulatory system. The "Active System" by itself is triggered by the resulting mean skin temperature, its time derivative and the hypothalamus temperature.

Preliminary study

To get a general idea of the different measurement methods used for whole body fat calculation and to analyze their sensitivity towards gender and age, we carried out a preliminary study. In total 84 subjects took part in the measurements. The subject group itself consisted of 38 female and 46 male participants. The female group was aged between 18-63 years, the age range of the male group reached from 21- 61 years. The measured parameters and the corresponding measurement equipment are listed in Table 1.

Table 1: Measured parameters and corresponding measurement equipment

PARAMETER	EQUIPMENT	MANUFAC.
Body height	gauging station	SECA 285
Body weight	gauging station	SECA 285
Waist circumference	tape measure	Slim Guide
Skinfold thickness	fat caliper	Slim Guide
BMI	gauging station	SECA 285

Calculation of total body fat content (BF)

For the calculation of the total body fat content we used a measurement method based on the determination of skinfold thickness at four selected measurement locations (Durnin & Womersley, 1974; Siri, 1961). The following measurement sites are prescribed by the measurement method: biceps (centre), triceps (centre), subscapula (diagonal fold) and suprailium (diagonal fold). The correlation between the sum of the four skinfolds and the gender and age related body density (Durnin & Womersley, 1974) finally allows the determination of the total body fat content (Siri, 1961).

Estimation of body fat distribution

The four locally measured skinfolds allow for the estimation of the distribution of the subcutaneous fat tissue at the upper part of the body. Thereby it is possible to reveal gender and age specific differences in local body fat accumulation. To be able to make statements towards the distribution of fat tissue across the total body, it is necessary to use additional measurement sites, which would require the application of further equations for the calculation of BF.

Bio-Impedance-Analysis (BIA)

To investigate the accuracy of our body fat measurements (Wölki et al., 2012), we carried out an additional Bio-Impedance-Analysis (InBody 720, Biospace Co., Ltd.). The InBody 720 is a highly accurate measuring device, which is used for whole body composition analysis and can be used within large experimental setups without running into logistical problems. Its measurement results linearly correlate with one of the golden standards in whole body composition analysis DEXA (Dual Energy X-ray Absorptiometry) with a correlation coefficient of $r = 0.984$. In contrast to most of the other BIA devices, the measurement results of InBody 720 are independent of empirical estimation variables, based on personal input parameters like gender, age or body type. For the measurement of body composition, the BIA-device makes use of the four-compartment method, which comprises total body water (intracellular water and extracellular water), protein, mineral and body fat (Biospace, 2004). In order to measure the whole body composition, the human body is split into five cylindrical segments, representing the limbs and the trunk. Each of those segments is analyzed separately by applying electrical currents of multiple frequencies (5-1000 kHz). As a result the InBody 720 delivers independent impedances for each of the five segments. The whole body composition is calculated as the sum and finally increases the accuracy of the measurement results. For further studies on the accuracy of InBody 720 refer to Malavolti et al. (2003), Salmi (2003) and Satorio et al. (2004). In this context we randomly chose five subjects and compared their BIA-results to their corresponding body fat calculation results, based on skinfold measurement (Figure 3).

Parameterization of the physiological part of the virtual thermoregulatory system

The parameterization of the virtual human thermoregulatory system is carried out with the body fat data resulting from our skinfold measurements. To be able to compare the original model to our modified model, body surface area, body height, skin and bone content were left unchanged. The BF is altered by the use of scaling factors, which directly influence the radii of the corresponding tissue layers of the virtual body segments. Like inside the real human physiology the metabolic rate ($M_{bas,0}$) and the total blood perfusion (CARDOUT) of the virtual human body are closely connected to the total BF. Due to the inner structure of the body segments a reduction of the outer radius of the muscle tissue leads to a decrease in muscle content followed by an increase in BF and consequently reduces $M_{bas,0}$ and CARDOUT.

RESULTS

Measurement of total body fat

Based on our skinfold measurement we defined a typical male (TMS) and a typical female subject (TFS). Figure 1 shows the corresponding gender specific results of the local measurement locations prescribed by Durnin & Womersley (1974).

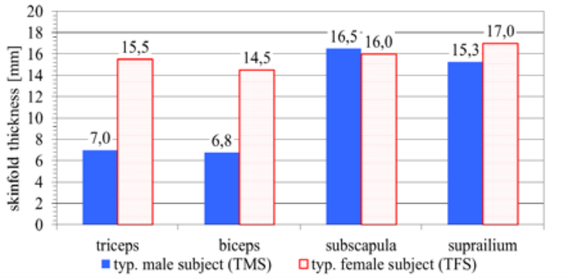

Figure 1: Gender specific skinfold thicknesses and corresponding measurement locations

The results clearly show a homogeneous distribution of the local skinfolds across the extremities (triceps 15.5 mm, biceps 14.5 mm) and the trunk (subscapula 16.0 mm, suprailium 17.0 mm) for the TFS. On the contrary, the distribution of the local skinfolds of the TMS is highly inhomogeneous and increases from the extremities (triceps 7.0 mm, biceps 6.8 mm) towards the trunk (subscapula 16.5 mm, suprailium 15.3 mm).

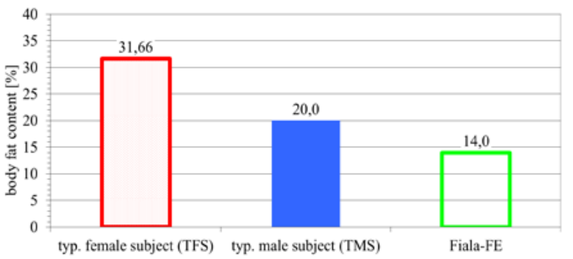

Figure 2: Comparison of body fat contents between TMS, TFS and Fiala-FE model

The comparison between the total BF of TMS, TFS and the original Fiala-FE model is shown in Figure 2. It becomes apparent, that the difference in BF between the TFS (31.66 %) and the Fiala-FE model (14 %) adds up to 17.66 %, which leads to a discrepancy of more than 56 %. On the other hand, the difference between the Fiala-FE model and the calculated BF of the TMS (20.0 %) is only 6 %, which corresponds to a deviation of 30.0 %.

Skinfold measurements versus BIA

Figure 3 shows the comparison between the BFs of the five randomly chosen subjects, based on skinfold measurement and BIA-analysis.

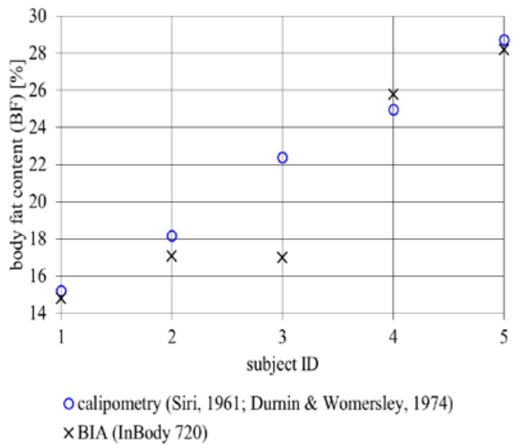

Figure 3: BF skinfold measurement vs. BF from BIA

Except for subject 3 ($BF_{skinfold\ measurement} = 22.41$ %, $BF_{BIA} = 17.0$ %), the BF results originating from skinfold measurement and the corresponding BIA-results are in good agreement.

Adaptation of the original Fiala-FE model to TFS

Based on the calculated body fat data of the TFS, we conducted a recalibration of the original Fiala-FE model. This step caused additional parameter adaptations inside the model's mathematical structure. The necessary parameter changes and the corresponding original data are shown in Table 2.

Table 2: Comparison between the calibration data of the original Fiala-FE model and TFS

PARAMETER	TFS	ORIGINAL FIALA-FE
body fat content (BF)	31.66 %	14.0 %
muscle content	24.04 %	43.21 %
body weight	70.31 kg	73.53 kg
body surface area (A_{sk})	1.86 m	1.86 m
basal metabolic rate ($M_{bas,0}$)	78.43 W	87.13 W
cardiac output (CARDOUT)	4.46 l/min	4.89 l/min

The reduction in muscle content from 43.21 % to 24.4 % along with the enhancement of BF (from 14.0 % to 31.66%) leads to a reduction in body weight (from 73.53 kg to 70.31 kg) and cardiac output (from 4.89 l/min to 4.46 l/min). The reasons for that are the differences in density and blood perfusion between muscle and fat tissue.

Simulation

The adjacent figures show the comparison of the simulation results of the original Fiala-FE model and the TFS model. To ensure the steady state of the simulation results, we chose the simulation time as 100.000 s. The corresponding boundary conditions of a simulation cycle are listed in Table 3 and originate from a thermal neutrality (PMV = 0) calculation according to Fanger's PMV (Predicted Mean Vote) index (DIN EN ISO 7730, 2006).

Table 3: Boundary conditions of a simulation cycle at thermal neutrality (PMV=0)

PARAMETER	MEANING	VALUE
rh [%]	rel. humidity	40
T_a [°C]	mean ambient air temperature	25.67
T_r [°C]	mean radiant tempera-ture	25.67
ε_{wall} [-]	emissivity of the sur-rounding wall surfaces	0.93
v_a [m/s]	mean air velocity	0.1
act [met]	activity level	1.2
Icl [clo]	clothing insulation value	0.38
PMV [-]	Predicted Mean Vote	0
t [s]	simulation time	100000

Figure 4 depicts the hypothalamus temperatures (T_{hy}) of both models in comparison.

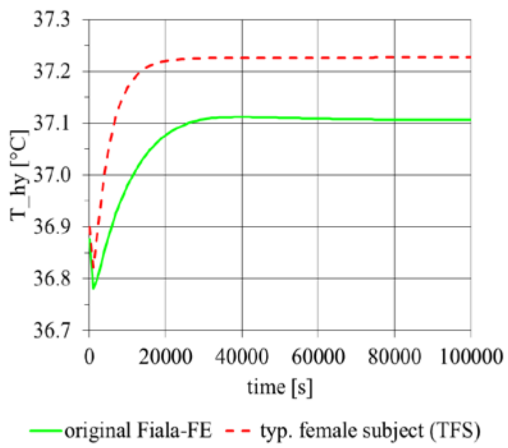

Figure 4: T_{hy} original Fiala-FE vs. T_{hy} TFS

T_{hy} shows a difference of 0.12 K after the simulations reached their steady state (T_{hy} of TFS = 37.22 °C, T_{hy} original Fiala-FE = 37.10 °C). Figure 5 contains the comparison of the corresponding mean skin temperatures (T_{skm}). It becomes apparent, that there is a difference of 0.52 K between the value resulting from the TFS model and the original Fiala-FE model.

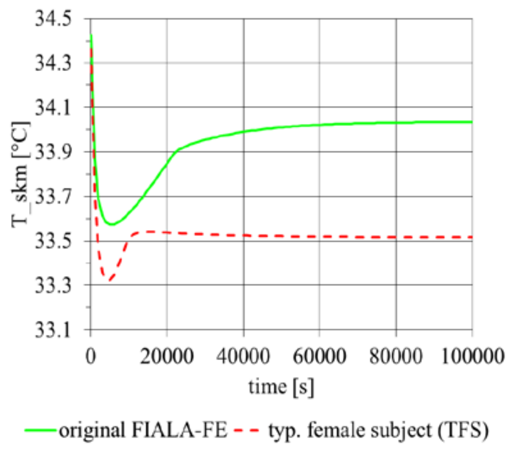

Figure 5: T_{skm} of TFS vs. original Fiala-FE

For a comparison of the total skin blood flow (SBF) see Figure 6.

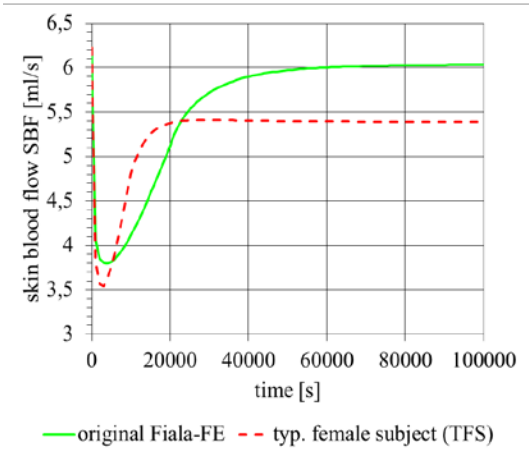

Figure 6: SBF of TFS vs. original Fiala-FE

It is shown that the skin perfusion of the original Fiala-FE model exceeds the TFS model to an amount of 0.64 ml/s.

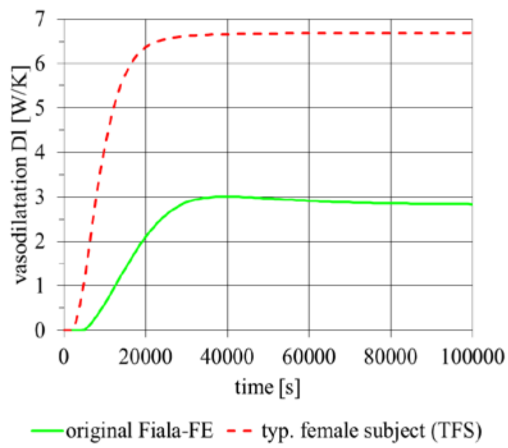

Figure 7: Dl reactions of TFS vs. original Fiala-FE

Figure 7 and Figure 8 show the vasomotive reactions of the two models. A difference in the onset of the vasodilatation (Dl) reactions (see Figure 7) becomes apparent. In addition the absolute value of the TFS model rises above the value of the original Fiala-FE model (DI orig. Fiala-FE = 2.83 W/K, DI TFS = 6.68 W/K), which leads to a difference of 3.85 W/K at the steady state.

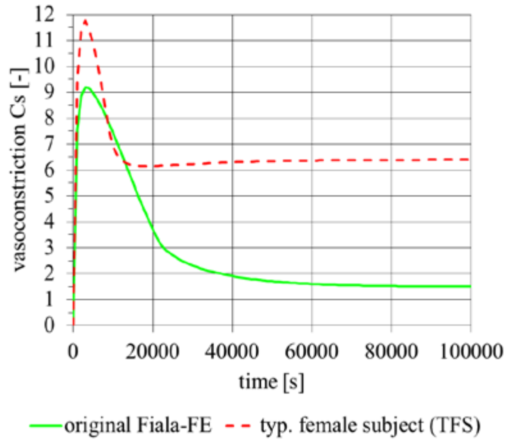

Figure 8: Cs of TFS vs. original Fiala-FE

The vasoconstriction (Cs) reactions of the TFS and the original Fiala-FE model are illustrated in Figure 8. The difference between the corresponding Cs-reactions is 4.91.

For the comparison between the separate cardiac outputs (CARDOUT) of the models see Figure 9. At the simulation's steady state a value of 5.16 l/min for TFS and 5.53 l/min for the original Fiala-FE model can be obtained.

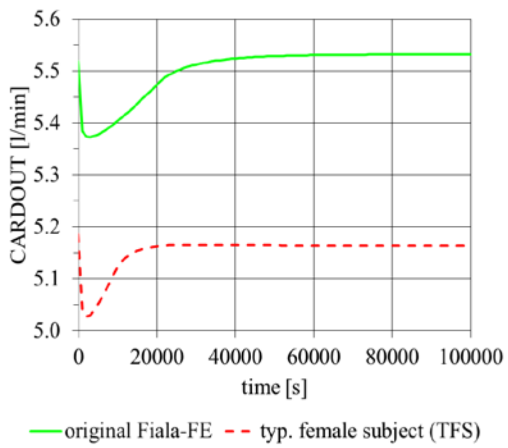

Figure 9: CARDOUT of TFS vs. original Fiala-FE

Figure 10 contains the difference in sweating rates (Sw). The results show an elevated Sw-reaction of 0.2 g/min for the TFS model. In addition a delay in the onset of Sw-rate of the original Fiala-FE model becomes obvious. It is shown, that the Sw-reaction for the TFS is initiated to a previous point in time.

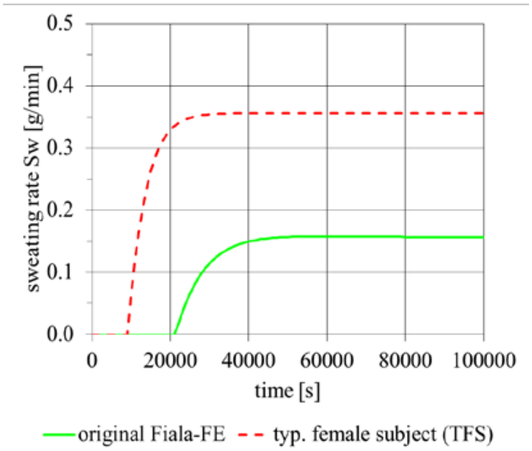

Figure 10: Sw of TFS vs. original Fiala-FE

Thermal comfort modelling

Quantitative effects of body fat variation on thermal sensation are illustrated in Figure 11 and Figure 12. The correlation between the mean skin temperatures (T_{skm}) and the hypothalamus temperatures (T_{hy}), respectively the PMV-values is based on a so-called inverse PMV calculation. For this reason we re-implemented Fanger's original PMV model (DIN EN ISO 7730, 2006). The PMV-model itself (Fanger, 1970) describes the energy balance of the human body and calculates the thermal sensation votes of a person influenced by the ambient climate of the corresponding building envelope. The input-parameters for Fanger's PMV-model are: ambient air temperature (T_a), mean radiant wall temperature (T_r), relative air velocity (v_a), relative humidity (rh), clothing insulation (Icl), basal metabolic rate (M) and workload (W). Before the start of the inverse PMV calculation, the parameterization of the virtual thermoregulatory system (Fiala-FE) has to be done. In this regard the parameters activity level (act) and clothing insulation (Icl) of the Fiala-FE model were defined and furthermore serve as constant input parameters for the inverse PMV calculation. M of Fanger's PMV model and act of the Fiala-FE model is set equal. Workload (W) was set to 0. In addition, the parameters rh and v_a were uniquely defined and again remain constant throughout the whole inverse-PMV-range calculation process. At least T_r and T_a are chosen as the only changeable input parameters for the re-implemented PMV-model. In order to define a homogeneous temperature distribution inside a building envelope, T_r and T_a were set equal and varied until the desired PMV value was reached. Both temperatures T_r and T_a together with the predefined constant ambient parameters v_a and rh now describe the ambient climate scenarios for the different PMV-values and represent the input parameters for the simulation setup of the Fiala-FE model. Finally, each of the different climate scenarios was simulated until the simulation reached a steady state, allowing for correlation of corresponding T_{skm} and T_{hy} values with the appropriate PMV-values.

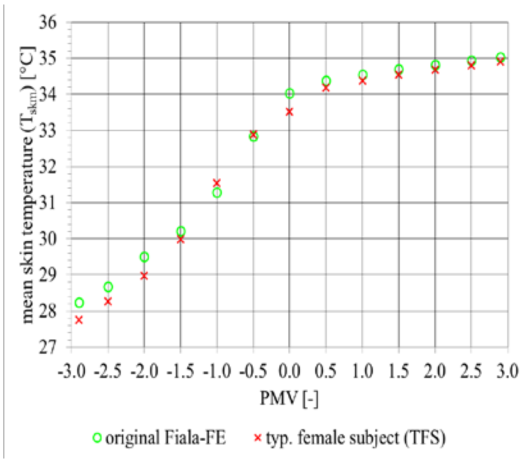

Figure 11: PMV vs. T_{skm}

A small difference in T_{skm} can be obtained across the entire PMV-range. The T_{skm}-values of the original Fiala-FE model are consistently higher than the T_{skm}-values of the TFS-model, except for PMV = -0.5 and PMV = -1.0.

For the correlation between T_{hy} and PMV see Figure 12.

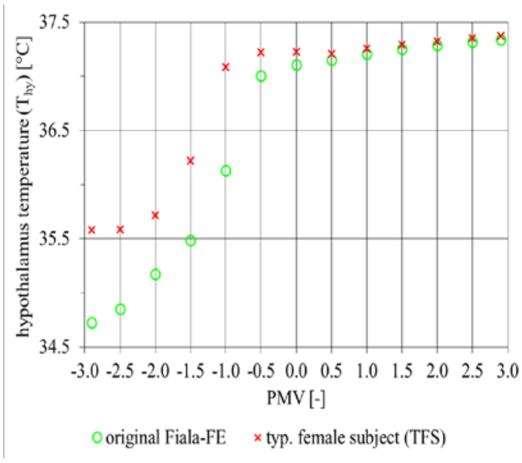

Figure 12: PMV vs. T_{hy}

It is shown, that the T_{hy}-values of TFS consistently exceed the values of the original Fiala-FE model across the entire PMV-range. In addition a totally asymmetric temperature spread concerning T_{hy} and T_{skm} for both models becomes apparent (see Table 4).

Table 4: ΔT_{skm} and ΔT_{hy} for TFS and orig. Fiala-FE

PMV-RANGE	MODEL	ΔT_{SKM} [K]	ΔT_{HY} [K]
0…-3	TFS	5.76	1.64
	orig. Fiala-FE	5.8	2.38
0…+3	TFS	1.38	0.15
	orig. Fiala-FE	0.99	0.23

DISCUSSION

The conducted skinfold measurements clearly show a gender specific difference in body fat content (Figure 1). The corresponding distribution of local body fat tissue is shown in Figure 2. Whereas males show an increased accumulation of fat tissue at the back (subscapula) and the iliac crest, the females' fat tissue is distributed homogenously across the body. This is in accordance with findings of Anderson (1999). Concerning our preliminary study, we made use of a skinfold measurement method, which considers four preselected measurement locations at the upper part of the subject's body to determine the corresponding body densities. The reason for the use of the four-point skinfold measurement method is the high accuracy of the body fat measurement results (Davidson et al., 2011; Durnin & Rahaman, 1967). The quality of the body fat caliper, the body side from which the measurement samples are taken and the consideration of skin thickness has no influence on the measurement results (Durnin & Womersley, 1974). In order to validate our measurement abilities and consequently the exactness of the body fat results, we performed an additional BIA-analysis (Figure 3) for which we arbitrarily chose five subjects of an independent group (3 male subjects, 2 female subjects). The comparison of the body fat results show good agreement, except for a single subject, whose skinfold measurement predicted a body fat content of 22.41 %, leading to a deviation of 5.41 % from the result of the corresponding BIA-analysis. Because of the small subject sample it is not possible to determine reasons for the difference at this state of research. An additional BIA-/caliper study, including a larger subject setup (150 subjects) is currently in progress and will be published elsewhere. In this context we are not only focusing on body fat content, but also on the muscle content, water content, mineral content and the distribution of such. The skinfold measurements will be carried out in addition and will be used as an indicator for local fat accumulation. Furthermore it will allow for the validation of our body fat calculations and the many different calculation equations (Keys et al., 1953; Siri, 1961; Durnin & Womersley, 1974; Davidson et al., 2011; Brožek et al., 1963; Deurenberg et al., 1991). From Figure 2 it becomes apparent, that the original Fiala-FE model was calibrated for a male individual. A first adaptation of the original Fiala-FE model to the total body fat content of the TFS indicates a dependency between body fat, hypothalamus temperature T_{hy} (Figure 4) and mean skin temperature T_{skm} (Figure 5). Due to the reduced heat conductance of fat tissue, the heat dissipation from the body core to the surroundings declines and finally causes an increase in T_{hy} (Anderson, 1999). A reduced muscle content leads to a decrease in total body perfusion (Figure 9, CARDOUT) and influences the total skin blood flow SBF. The reason for that is the quasi-linear correlation between SBF and muscle blood flow (Fiala et al., 2001). In this context the TFS model shows a decreased skin blood flow (Figure 6, SBF), an increased vasodilatation (Figure 7, Dl) and an increased vasoconstriction (Figure 8, Cs) compared to the original Fiala-FE model. From a physiological point of view, an increase in body fat content would cause an increase in T_{hy} in consequence of the reduced ability for heat dissipation from the body's core to the surroundings. To be able to compensate the increasing body core temperature, the skin blood flow would rise (Anderson, 1999). This is in accordance with the increased vasodilatation reaction of the TFS model and the corresponding increase in SBF. In addition, the onset of vasodilatation starts at an earlier simulation stage as a consequence of the higher T_{hy}. The SBF of the TFS model shows a lower absolute value compared to the original Fiala-FE model, because of the reduced muscle content and the accompanying reduction in total CARDOUT. At the same time the vasoconstriction (Cs) reaction of the TFS model rises above the Cs of the original Fiala-FE model. This is due to the strong dependency between T_{skm} and Cs. The reduced T_{skm} temperature of the TFS model leads to the higher relative Cs reaction of the TFS model. In addition the sweating reaction (Sw) of the TFS model starts at an earlier point in time and rises above the level of the original Fiala-FE model. Physiologically this is caused by the reduced ability of heat dissipation, because of the insulation effect of fat tissue (Anderson, 1999).

In terms of thermal comfort assessment we used the well-known PMV-model (DIN EN ISO 7730, 2006; Fanger, 1970) and correlated it with physiological body signals from TFS and original Fiala-FE model. According to Fanger's theory the models would have the same thermal sensation votes at the same level of activity. The simulation results depicted in Figure 11 and Figure 12 clearly show different levels of thermoregulatory activity of the two models, reflected in the various disparities in physiological signals (e. g. Sw, Dl, Cs, SBF etc.) at the same ambient conditions. Due to this, the use of comfort models, which simply consider the energy balance of the body for comfort assessment, are not sufficient, especially with respect to non-uniform, dynamic ambient conditions, in which the dynamic physiological reactions could have an increasing influence on thermal sensation and thermal comfort (Huizenga et al., 2001; van Marken Lichtenbelt et al. 2007).

CONCLUSION

Our preliminary study reveals big differences in body fat content between females and males. We could show that the physiological calibration data of the original Fiala-FE model (Paulke, 2007) is designed for a male subject and significantly differs from the data of a real female physiology. The adaptation of the original model to the dataset of the typical female subject (TFS) goes along with lots of additional parameter adjustments and demonstrates the high model complexity. Corresponding simulation results indicate a relation between body fat content and thermal comfort, reflected in the different levels of thermoregulatory activity of the two compared models. This is in accordance with findings by van Marken Lichtenbelt et al. (2007). The use of detailed simulation models, able to reproduce individual physiological reactions with high accuracy, can help to understand the complex field of human-centered comfort modeling and can support the invention of control strategies for energy saving and consequently cost effective buildings.

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