Proceeding of: Indoor Air Conference, June, 2011, Austin, TX

Individualisation of virtual thermal manikin models for predicting thermophysical responses

Daniel Wölki[1,*], Christoph van Treeck[1], Yi Zhang[2], Sebastian Stratbücker[1], Sandeep R. Bolineni[1] and Andreas Holm[1]

[1]Fraunhofer Institute for Building Physics (IBP) Holzkirchen, Dept. Indoor Environment, Germany
[2]Institute of Energy and Sustainable Development, De Montfort University, Leicester, UK

[*]*Corresponding email: daniel.woelki@ibp.fraunhofer.de*

SUMMARY
We identify key parameters to adapt physiological models to represent different morphological groups of individuals in terms of thermo-physical responses of the body to thermal conditions. For estimating the human thermoregulation responses towards ambient microclimate, a finite element implementation of a mathematical thermoregulation model is used. The specific implementation allows the modification of parameters which affect the thermoregulation. Relevant parameters are identified to adjust the model in terms of morphological parameters while some of the anthropometrical constraints are obtained from an ergonomic model. In order to calculate the heat transfer between skin surface of the virtual manikin and its surroundings, different computational codes, coupled with a co-simulation middleware application, are used.

IMPLICATIONS
Today, models for predicting thermo-physiological responses of the human body including thermoregulation consider a standard morphology. Yet, only a few authors address the issue of individualisation. To transfer existing models to other morphological groups, further research is necessary to diversify key parameters in terms of model calibration.

KEYWORDS
Anthropometrics, human thermoregulation, morphology, thermal sensation, virtual physiological human

INTRODUCTION
To an increasing tendency, simulation tools are used which contain mathematical models to represent the human thermoregulatory system as a method for designing human centred indoor environments in terms of thermal comfort. In building design the most commonly used approach for evaluating thermal comfort is based on the pioneering work of Fanger (1970). This approach is, however, restricted to steady state conditions near thermal neutrality and is only limited applicable to transient or non-uniform thermal conditions. Thermal comfort prediction to non-uniform and transient conditions is significant for the rail, aircraft and automotive industries. Passenger cabins, for example, are confined spaces, where heat transfer processes like convection, thermal radiation and heat conduction are causing local thermal asymmetries. To consider such microclimates and to correlate with thermal comfort and sensation, detailed human thermoregulation models have been suggested since the 1960's. Such thermo-physiological models predict dynamic responses of the body to a wide range of ambient conditions (Fiala et al. 1999, 2001; Huizenga et al. 2001, Stolwijk, 1971; Tanabe, 2002; Yokoyama, 1997). For modelling heat exchange between body and environment, pre-

defined heat transfer coefficients or detailed computational methods are used. For example, Cropper et al. (2009), Streblow et al. (2008) and Zhang and Tong (2008) demonstrated a related integrated study.

Following our previous work (van Treeck et al. 2009), we developed a co-simulation adaptation platform (CoSimA+), which serves as middleware for coupling numerical models and experimental tools such as sensor hardware to support human-centred indoor thermal quality performance analysis. As part of our project this paper addresses the individualisation of a finite element representation of the multi-segmental thermoregulation model of Fiala et al. (1999, 2001), which is originally calibrated for an average human morphology (Paulke, 2007). In order to represent different morphological groups and, hence, to improve the predictability (van Marken Lichtenbelt et al. 2007) of the parametric model towards thermal comfort and thermal sensation, it is necessary to indentify key parameters and their mutual dependencies.

STATE-OF-THE-ART

Havenith (2001) reports the influence of individualisations on prediction of human thermoregulatory response to heat stress (workload) under hot-dry, warm-humid and cold conditions. For his investigations he chose a 2-node model, based on the former work of Gagge et al. (1986) extended by a clothing model following Lotens (1993). His model contains additional input parameters represented by body mass (m), body fat layer thickness, body surface area (A_D), oxygen uptake (V_{O2max}), as index for the physical state of the body, and the acclimatisation state. For validation, the original and the modified model are compared towards predictability according to body core temperature gained from former experiments. His study reveals that influences of the different individualisations strongly depend on environmental conditions and that further research is necessary towards the effect of body fat under cold conditions.

Van Marken Lichtenbelt et al. (2007) investigate the individualisation of Fialas' 15-segment model (1999, 2001) for predicting responses of subjects exposed to cold air. For the model validation they carried out experiments with real subjects and performed a statistical analysis of their simulation results. The individualisation considers differences in anthropometric data of the subjects taking part in the study, using a scaling factor in order to adapt the body dimensions to the individual characteristics. Additionally body fat content (BF%) was calculated and modified by rescaling the radii of the corresponding tissue layers except for the skin. Resting metabolic rate (RMR) and actual metabolic rate (MR) were calculated for each subject and modified inside the mathematical structure of the virtual manikin model. For model validation, the mean skin temperature ($T_{sk,m}$) was used to quantify the recalibrated model towards measurable subject data. The researchers found out, that MR has the highest impact of all parameters on $T_{sk,m}$. The combination of BF% and MR additionally influences $T_{sk,m}$ on a high level, whereas body size plays a minor role.

The objectives of Schellen et al. (2010) are the identification of differences between young adults and elderly in thermal comfort, productivity and thermal physiology under moderate temperature drifts. For this reason they carried out experiments where they exposed two different subject groups (age 22-25 and age 67-73) to well defined climate scenarios. The researchers investigated skin and body core temperature. For estimating thermal comfort, the subjects filled in questionnaires. Schellen et al. (2010) found, that thermal sensation votes are in general 0.5 scale points lower for the elderly than for their younger counterparts, additional thermal comfort votes showed the same trends. The authors conclude, that these differences might be explained by a reduced thermoregulatory response, indicated by a lower skin temperature correlated with the differences in vasomotion. They also remark, that the efficiency of cold and warm-defence mechanisms decrease and can be connected with reduced muscle mass and metabolic rate.

Novieto and Zhang (2010) study the possibility of adapting the IESD-Fiala model to an aged human body. They focus on three parameters obtained from literature, playing a major role in terms of ageing effects. These parameters are basal metabolic rate (BMR), cardiac output (C.O.) and body weight (BW). As a first approach they varied each parameter separately in their physiological range of -20% - +20% compared to the standard human manikin model and calculated the ambient and mean radiant temperature, necessary for keeping the model in thermal neutrality (no intervention of the active system). In a second step they focussed on dynamic thermal sensation (DTS) and thermal comfort prediction (PPD). Their results reveal that BMR is the main responsible factor for changes in thermal comfort requirements. The combination of BMR, C.O. and BW show a high influence on local comfort concerning skin areas directly exposed to thermal ambient conditions.

METHODS

Materials

Identification of human key parameters, characterising different morphological groups, is the main focus of this paper. We use a finite element based (FIALA-FE) implementation of Fiala's thermoregulation model (Paulke, 2007), calibrated for an average European (male) adult in terms of body weight (73.53 kg), body fat content (14.43%) and DuBois area (1.85 m^2). Considering individual tissue layer blood perfusion and metabolic rates, the FE-model calculates the corresponding basal metabolic rate (87.12 W) and the resting cardiac output (4.89 L/min).

Finite element approach FIALA-FE

FIALA-FE consists of two interacting parts, a controlled system (*passive system*) and a controlling system (*active system*). The *passive system* models the body and thermo-physiological processes, based on the *bioheat equation* (Pennes, 1948). The body is divided into 19 cylindrical or spherical elements consisting of layers, representing different kinds of tissue like bone, muscle, fat and skin. An additional clothing layer is also considered. To account for body and environmental asymmetries, the 19 body elements are split into sectors (*anterior*, *posterior*, *inferior*). The *active system* represents the bodies' thermoregulation mechanisms consisting of sweating, shivering, vasoconstriction and vasodilatation, affecting the thermo-physical processes of the *passive system*.

In this work, we make use of file-based interface via scripting to interact with the FIALA-FE core solver. The THESEUS interface follows to modify and to create own manikins, if physiological parameters are known (Paulke, 2007; van Treeck et al. 2009).

Procedure

We are identifying characteristic human key parameters representing the differences in human morphology with the help of literature. Based on these findings, we check the palpability of these characteristics inside the mathematical structure of FIALA-FE to adapt the model to the resultant set of parameters. Furthermore, we define environmental scenarios (Fiala et al. 1999) to carry out a sensitivity analysis (Novieto and Zhang, 2010) to evaluate the corresponding impact on the dynamics of the thermoregulatory system. The validation of the individualised "new model" will be done by experimental investigations in a later stage. In our future work, the individualisation process itself will be accomplished through a graphical user interface (GUI), using our CoSimA+ platform (Stratbücker et al. 2010). This allows a fast modification of the model and a realtime validation of the simulation results, when coupled with experimental tools or other software tools calculating heat transfer, shortwave radiation and clothing issues (see Figure 1).

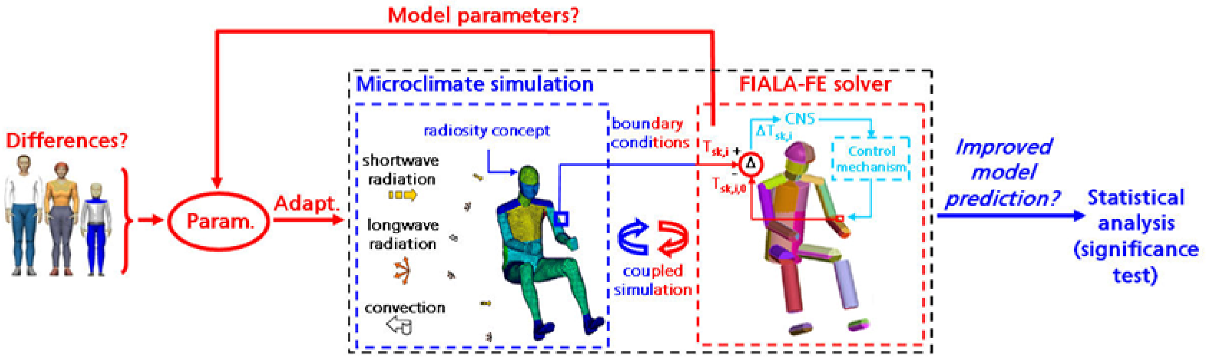

Figure 1. Concept for adapting FIALA-FE to other morphological groups

RESULTS

An intensive literature research revealed three promising parameters that might be able to characterize the main differences in human morphology. Table 1 summarizes our findings and shows mutual influences and corresponding literature sources.

Table 1. Most promising human key parameters and their mutual influences

Parameter	Model parameters	Mutual physiological influences	Literature source
BMR	$M_{bas,0}$	cardiac output, body size body constitution, gender, age, acclimatisation state, sweating rate, shivering rate, vasomotion	Havenith (2001), Schellen et al. (2010), Schofield (1985), Novieto and Zhang (2010), van Marken Lichtenbelt et al. (2007)
B.C.	r, A_D, L	gender, age, body mass, body fat content, muscle content, body size, DuBois area	Havenith (2001), Tikuisis et al. (1990), van Marken Lichtenbelt et al. (2007)
C.O.	CARDOUT	body size, gender, age	Novieto and Zhang (2010)

To date we were investigating the two parameters BMR and C.O. to quantify our findings from literature (Table 1). For this we carried out a sensitivity analysis using FIALA-FE (Figure 2).

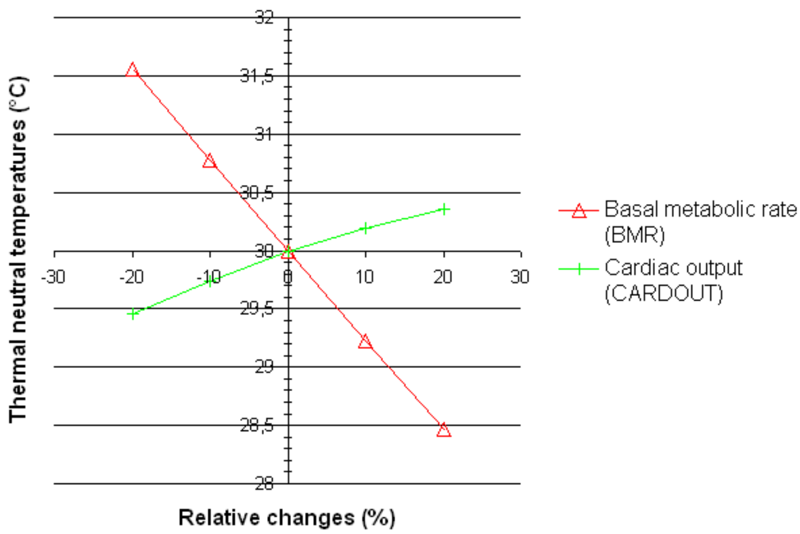

Figure 2. Sensitivity analysis towards thermal neutrality carried out with THESEUS-FE

The corresponding procedure can be extracted from Novieto and Zhang (2010), which used the IESD-Fiala model to study the effect of ageing on thermal comfort. Varying the parameters BMR and C.O. of the "original" model in a range of -20% - +20% shows, that FIALA-FE has the highest sensitivity towards BMR. In this case, sensitivity is expressed in the high deviation of the modified model (±1.5 °C) towards thermal neutral ambient temperatures, needed to maintain the body core temperature on a constant level of about 36.89 °C. Modifying C.O. inside the mathematical structure of FIALA-FE shows also a considerable sensitivity, but reveals a contrary behaviour compared to BMR.

DISCUSSION

The results show the high complexity of the human thermoregulation system itself. As others concluded, a huge part of the human thermoregulation is still unknown and can lead to systematic errors concerning the prediction of individual thermoregulatory responses (Havenith, 2001; van Marken Lichtenbelt et al. 2007; van Treeck et al. 2009). Based on a literature survey we further investigate the three parameters body constitution, basal metabolic rate and cardiac output. A first sensitivity analysis revealed that BMR and C.O. show considerable effects on the thermoregulatory behaviour of our thermal manikin (Figure 2). Furthermore BMR and B.C. have similar impacts on the human thermoregulation system (Novieto and Zhang, 2010). However, BMR seems to play the major role towards morphological differences (Havenith, 2001; Novieto and Zhang, 2010; Schellen et al. 2010; van Marken Lichtenbelt et al. 2007). One reason might be the various parameters, included in forming the basal metabolic rate (Table 1). In addition, the individualisation asks for subject experiments in terms of model validation. For this reason, the level of measurement accuracy and, thus, the predictability of the model will strictly be bound to the measuring methodology. An additional source of error implies the use of indirect measurement techniques which is obviously inevitable, because parameters of interest are not directly measurable. The accuracy of the respective engineering model clearly is a trade-off between physical level-of-detail for predicting human thermoregulation and the required resolution for simulating physiological responses in terms of comfort assessment.

CONCLUSIONS

We have identified relevant key parameters towards individualisation of a thermoregulation model to represent different individuals. Further work will comprise a detailed sensitivity analysis to quantify the impact of parameter variations, the development of a GUI-interface for model individualization as well as validation work involving experiments with subjects. We currently develop interfaces to other computational codes for integrated comfort analysis using our co-simulation platform (Stratbücker et al. 2010).

ACKNOWLEDGEMENT

This work is supported by the Fraunhofer Internal Programs under Grant No. Attract 692 329.

REFERENCES

Cropper P., Yang T., Cook M., Fiala D., and Yousaf R. 2009. Simulating the effect of complex indoor env. cond. on human therm. comf.. In: *Proc. Build. Sim.*, Glasgow, UK.

Deurenberg P., Weststrate and J.A., Seidell J.C. 1991. Body mass index as a measure of body fatness: age- and sex-specific prediction formulas. *Br J Nutr*, 65:105-114.

Fanger P.O. 1970. *Thermal Comfort*. Copenhagen: Danish Technical Press.

Fiala D., Lomas K.J., and Stohrer M. 1999. A computer model of human thermoreg. for a wide range of env. conditions: the passive system. *J Appl Physiol*, 87:1957-1972.

Fiala D., Lomas K.J., and Stohrer M. 2001. Computer pred. of human thermoreg. and temp. responses to a wide range of environmental conditions. *Int J Biometeorol*, 45:143-159.

Gagge A.P., Fobelets A.P., and Berglund L. G. 1986. A standard predictive index of human response to the thermal environment. *ASHRAE Transactions*, 92, 709-731.
Havenith G. 2001. Individualized model of human thermoregulation for the simulation of heat stress response. *J Appl Physiol*, 90:1943-1954.
Huizenga C., Hui Z., and Arens E. 2001. A model of human physiol. And comfort for assessing complex thermal env.. *Bldg. and Env.*, 36, 691-699.
Lotens W.A. 1993. Heat Transfer from Humans Wearing Clothing. *Ph. D. Thesis*, Delft (Netherlands), Delft Univ. of Technology.
Novieto D.T. and Zhang Y. 2010. Therm. Comf. Impl. of the Aging Eff. on Metabol., Card. Out. and Body Weight. *Proc.: Adapt. to Change: New Thinking on Comf.*, Windsor (UK)
Paulke S. 2007. Finite element based implementation of Fiala's thermal manikin in THESEUS-FE. In: *EUROSIM 2007*.
Pennes H. 1948. Analysis of tissue and arterial blood temperatures in the resting human forearm. *J Appl Physiol*, 1 (2), 93-122.
Schellen L., van Marken Lichtenbelt W.D., Loomans M.G.L.C., Totfum J., and de Wit M.H. 2010. Differences between young adults and elderly in thermal comfort, productivity, and thermal physiology in response to a moderate temperature drift and steady-state condition. *Indoor Air 2010*, 20, 273-283.
Schofield W.N. 1985. Predicting basal metabolic rate, new standards and review of previous work. *Human Nutrition: Clin Nutr*, 39C, Suppl. 1, 5-41
Stolwijk J.A.J. 1971. A mathematical model of physiol. temp. reg. in man. *Contractor report NASA CR-1855*, Nat. Aeronautics and Space Admin., Washington D.C..
Stratbücker S., and van Treeck C. 2010. CoSimA+ Co-simulation adaptation platform, Fraunhofer-Institut for Building Physics, *IBP Report*, 37-2010.
Streblow R., Müller D., and Gores I. 2008. A coupled simulation of the therm. environment and thermal comfort with an adapted Tanabe model. In: *Proc. IndoorAir*, Denmark.
Tanabe S.-I., Kobayashi K., Nakano J., Ozeki Y., and Konishi M. 2002. Evaluation of thermal comfort using combined multi-node thermoregulation (65MN) and radiation models and computational fluid dynamics (CFD). *Energy and Buildings*, 34:637-646.
Tikuisis P, Bell D.G., and I. Jacobs 1990. Shivering onset, metabolic response, and convective heat transfer during cold air exposure. *J Appl Physiol*, 70(5):1996-2002.
van Marken Lichtenbelt W.D., Frijns A.J.H., van Ooijen M.J., Fiala D., Kerster A.M., and van Steenhoven A.A. 2007. Validation of an individualised model of human thermoregulation for predicting responses to cold air. *Int J Biometeorol*, 51:169-179.
van Treeck C., Frisch J., Pfaffinger M., Rank E., Paulke S., Schweinfurth I., Schwab R., Hellwig R., and Holm A. 2009. Int. thermal comfort analysis using a parametric manikin model for interactive simulation. *J Building Performance Simulation*, 2(4):233-250.
Yokoyama S., Kakuta N., and Ochifuji K. 1997. Development of a New Algorithm for Heat Transfer Equation in the Human Body and its Appl.. *Human Sci.*, 16, 153-159.
Zhang H., Arens E., Huizenga C., and Han T. 2010. Thermal sensation and comfort models for non-uniform and transient env., Parts I-III. *J Building and Environment*, 45, 380-410.
Zhang Y., Yang T. 2008. Simulation of human thermal response in a confined space. *Indoor Air*, Copenhagen (Denmark).