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Thermal Comfort Implications of the Aging Effect on Metabolism, Cardiac Output and Body Weight

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Abstract

The challenges of population aging call for research on the impacts of age-related changes in the human body and its physiological function, on the thermal comfort requirements of the older people. Detailed human thermoregulatory models have been used to predict physiological responses and comfort of a typical person in a wide range of environmental conditions. This paper investigates whether an established human model, i.e. the IESD-Fiala model, can be adapted to represent an aged human body. Three parameters that show significant change with aging have been identified from literature. These are basal metabolic rate (BMR), cardiac output (C.O.) and body weight (BW). Sensitivity tests and case studies were used to demonstrate the impact of aging on these parameters and its thermal comfort implications. For example, a transient simulation showed that due to reduced metabolism, excessive exposure of an older person to a cold environment might lead to overcooling of the body, which cannot be rectified by putting on warm clothes.

Keywords: Aging, thermal comfort, basal metabolic rate, cardiac output, body weight.

Introduction

Aging of populations around the world (ILC, 2009) is a significant challenge in the 21st century. To the individuals, old age is linked to the diminishing ability to adapt to varying environmental conditions. Older people are more prone to thermal-related comfort and health issues, including hypo- and hyperthermia. Thermal comfort, or the lack of it, is well understood to be one of the most significant restrictors to the health and general wellbeing of the older people. In order to create conducive built environments that satisfy the needs of the future users, it is essential to establish the relationship between aging and thermal comfort requirements, so that designers can have a tool to design and retrofit buildings to meet the demand of the changing demography. There are two questions have to be addressed, however: (1) what are the effects of aging on the human body, in terms of thermal properties and thermoregulatory functions? In addition, (2) how do we model the age-related changes to capture the impact of aging on thermal comfort requirements?

Thermal comfort models, especially detailed human models, have been developed to predict thermal physiology and comfort of typical individuals of the working population (Fiala, 1998). Despite the apparent benefit of using a similar approach to study thermal comfort issues of the older population, such studies have not yet been reported. It is also unproven whether the existing human models can be adapted to represent older population by adjusting the relevant parameters. This paper presents the initial investigation into the aging effect on some of the physical and physiological properties of the human body, including basal metabolic rate, cardiac output and body weight, and their implications on the thermal comfort.

Aging and Comfort

As the human body ages, gradual changes occur in the body and its functions such as the cardiovascular functions, muscle mass, skin structure and functions, sensory and regulatory responses, basal metabolism, and body composition (Rodeheffer, 1984, Hyatt, 1990, Aniansson, 1986, McGavock and Levine, 2009). Together, these changes lead to a diminished physiological reserve (Aalami, 2003, Grundy, 2006) for adaptation to environmental conditions. In extreme cases, such as during extreme weather events, this may result in excessive thermal strain on the body to maintain constant internal temperature. As a result, health and even life may be at risk. In August 2003, more than 2000 deaths were attributed to the heat wave in England and Wales (Kovats et al., 2006). During the period, excess mortality was 33 per cent in those aged 75 and over, compared to 13.5 per cent in the under-75 age group. Statistics in France showed a strong correlation between excess death and age during the heat wave. The excess mortality was estimated at 20% for those aged 45-74 years, at 70% for the 75-94 year age group, and at 120% for people over 94 years (Pirard, 2005). In contrast, there was no evidence of excess mortality in infants and children.

Despite the extreme events like the heat waves, excess mortality amongst the elderly mainly occurs in the winter months, when lack of warmth and hypothermia pose a major threat (Healy, 2003). Reduced metabolism and activity level were often identified as the main contributor to the loss of tolerance to low temperature. Research in thermal physiology and medical studies has found that changes in many departments of the human body may contribute to the reduction in thermoregulatory functions. Older persons are at increased risk of both hypothermia and hyperthermia when exposed to extreme temperatures(Someren, 2007), which may be linked to structural changes in the skin as well as less effective neural regulation of blood flow and sweating (Rooke, 1994). The peripheral thermo-sensitivity appears to be progressively attenuated with age (Anderson, 1996), and elderly individuals are at a disadvantage with regard to defending against core temperature perturbations.

Paradoxically, past studies found little evidence that older people would prefer higher temperature for thermal neutral conditions (Collins, 1980). Lab-based experiments concluded that, once the metabolic rate has been taken into account, the differences in neutral temperature among different age groups are insignificant. Given the range of changes that aging involves, it is likely that other factors act in conjunction with the metabolic rate in determining the neutral temperature. More importantly, the question remains unaddressed that what will happen when the environmental condition deviates from the neutral condition, i.e. can the aged thermoregulatory mechanisms cope with the daily situations as usual. A holistic approach that connects all the factors with a detailed human model has to be adopted in studying the complex relations between aging and thermal comfort.

Methodology

In this paper, the IESD-Fiala model was used for investigating the impact of age-related changes in basal metabolic rate (BMR), cardiac output (C.O.), and body weight (BW). Like most human thermoregulatory models, the Fiala model regards the human body as two interacting systems, i.e. the controlled passive system (body structure) and the controlling active system (the thermoregulatory functions). The passive system is a multi-segmental, multi-layered representation of the human body with spatial subdivisions. The body is idealised as 19 spherical and cylindrical elements built of annular concentric tissue layers with the approximate physical properties and thermo-physiological functions. Individual tissue layers are subdivided into spatial sectors to enable detailed modeling of environmental asymmetries. The active system models the thermoregulatory functions of the human body, including vasoconstriction/vasodilatation, sweating and shivering.

The aging impact on the parameters of the passive system is the focus of this paper. The original model represents a typical person (an adult European male) with respect to body weight (73.5 kg), body fat content (14%weight), and DuBois area (1.86 m^2). The physiological data aggregates to a basal metabolic rate of 87W and resting cardiac output of 4.7 L/min (Fiala 1998). Sensitivity test of the model to BMR, C.O. and BW was first carried out to evaluate the impact of each factor on thermal neutral temperature of the body. Combined effects of age-related BMR, C.O. and BW changes on thermal comfort were subsequently demonstrated with two case studies. Statistical reduction in BMR, C.O. and BW of the older population group (sourced from literature survey) was used to represent an aged human body. How the new model respond, in terms of overall and local thermal comfort, to the “neutral” environmental conditions for a typical person is then analyzed with quasi steady-state simulations.

The new model was also used to study thermal comfort in transient conditions, which had not been possible without detailed human models. An experiment was designed to demonstration a plausible scenario that an old person exposes to (moderate) cold environment. The effect of cloths change and re-warming are simulated.

Sensitivity test

The purpose of the sensitivity test was to quantify the relative impact of variation of individual parameters. Cardiac Output (C.O.), Basal Metabolic Rate (BMR), and Body Weight (BW) were varied independently from -20% to +20% compared to the standard Fiala model. Also considered is the variation of body weight whilst normalized BMR (W/kg weight) and Basal Blood Perfusion Rate (L/min/kg weight) were kept constant. The parameter was assumed to represent the “SIZE” of an individual, e.g. that a large person may have proportionally higher total metabolism and cardiac output.

The first test (Figure 1) was the calculation of the neutral ambient temperature of a reclining human body. The unclothed resting human body was assumed to have an activity level at the basal metabolic rate. The required ambient air temperature (also the mean radiant temperature) at which the body can maintain a constant core temperature at 37.0°C without resorting to thermoregulatory actions was calculated. Compared to the reference condition, higher neutral temperature means that either the body was rejecting more heat than required to the environment (due to increased C.O. and BW), or the body was producing less heat than normal (due to reduction in BMR or SIZE). It was clear to see that BMR has the most significant impact on the neutral temperature. As the human body ages, the effect of BMR reduction is attenuated to some extent by the simultaneous reduction of C.O. and BW.

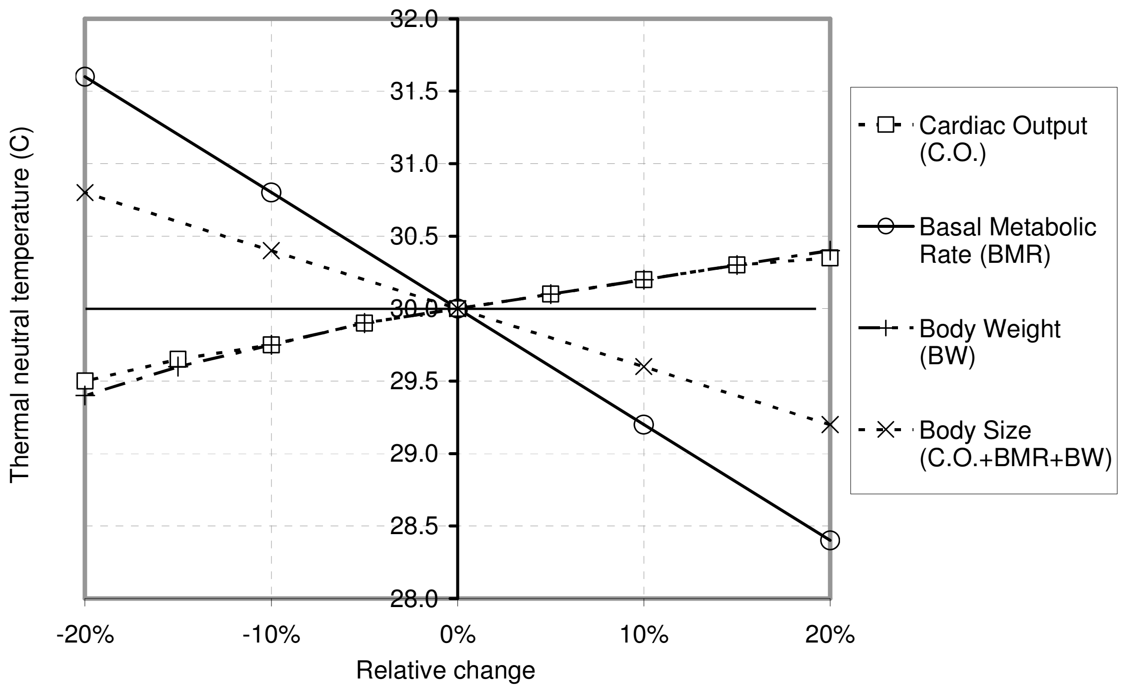

Figure 1. Sensitivity of thermal neutral ambient temperature to BMR, C.O. and BW

Figure 2 and 3 show the sensitivity of Dynamic Thermal Sensation (DTS) and PPD to the changes of the parameters. A neutral indoor condition (Ta = MRT* = 23.8°C, Va = 0.1m/s, RH** = 40%, 0.62clo, 1.1met) was chosen; and the overall dynamic thermal sensation and PPD predictions from the model were collected after 180min exposure to the environment. The results confirm our expectations, i.e. individuals with lower BMR and SIZE, or higher C.O. and BW tent to feel cooler under the same environmental conditions. The charts also show that the models are more sensitive to cooling than warming, which requires further investigation.

* Mean Radiant Temperature
** Relative Humidity

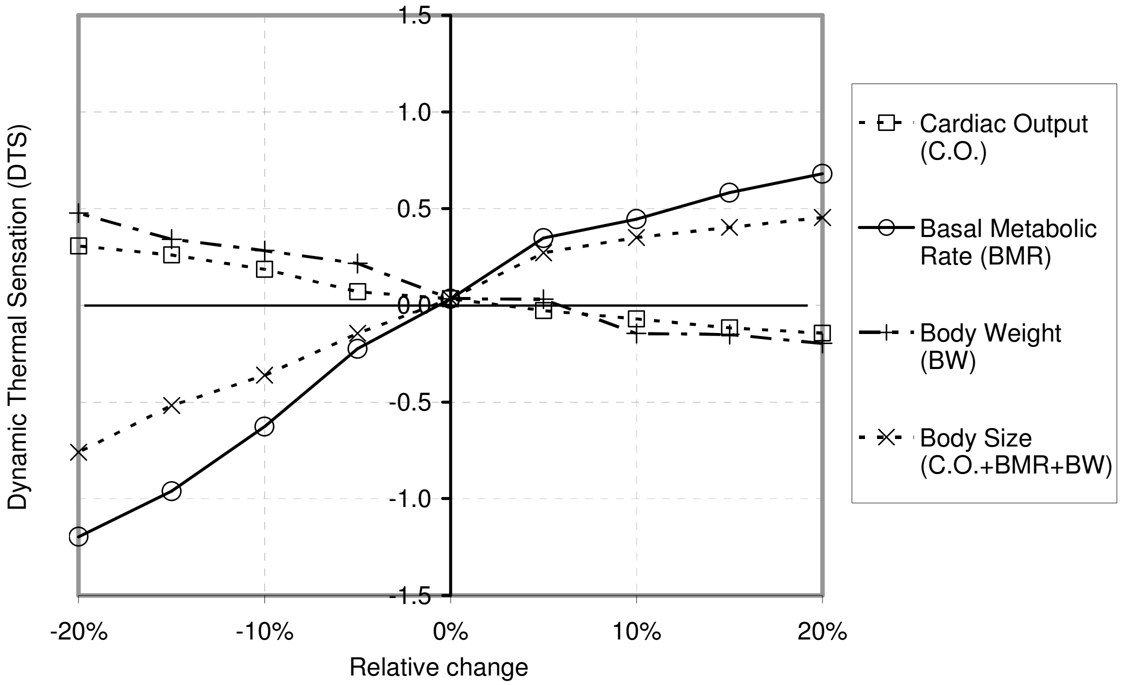

Figure 2. Sensitivity of thermal sensation vote to BMR, C.O. and BW
(Ta = MRT = 23.8°C, Va = 0.1m/s, RH = 40%, 0.62clo, 1.1met)

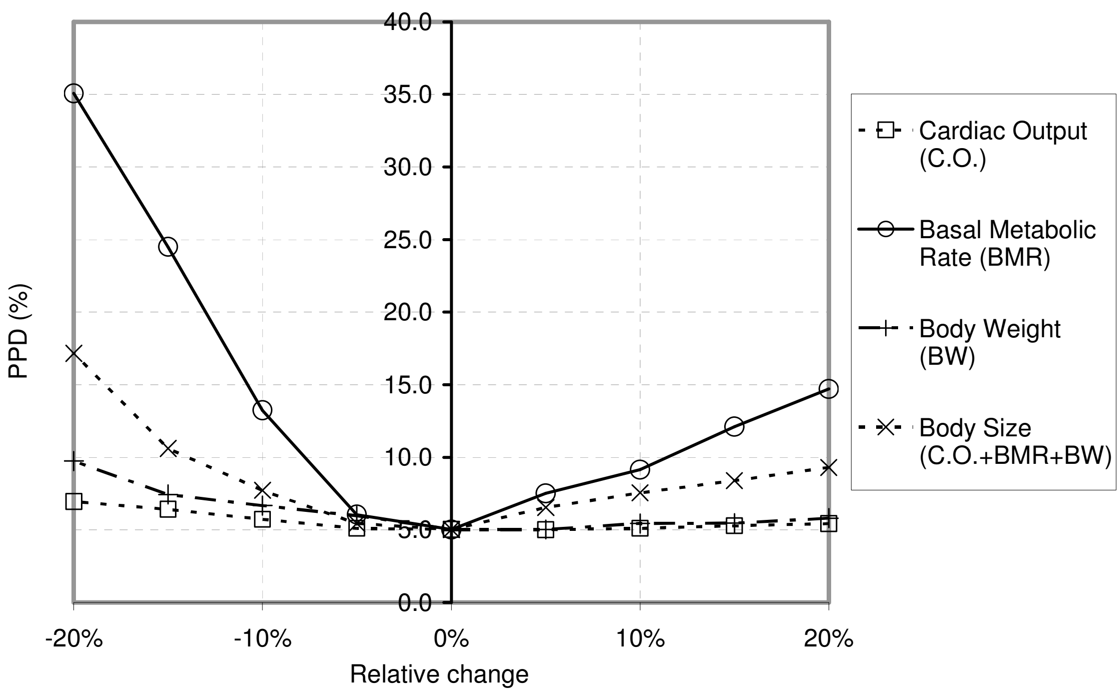

Figure 3. Sensitivity of PPD to BMR, C.O. and BW
(Ta = MRT = 23.8°C, Va = 0.1m/s, RH = 40%, 0.62clo, 1.1met)

Model of a typical old person

The present Fiala Model represents an average European adult male with the following values for the main parameters identified for modification, i.e. Body weight (73.5 kg), basal Cardiac Output of 4.7 (L/min) and Basal Metabolic Rate (86.6 watts). In order to develop a model representative of the older population, the 2050 world projected population figures (Holtz-Eakin 2005) were used to determine the median age of the group between 65yrs – 100yrs. The resultant 75.1yrs thus serves as the reference age of the older population for determining the Basal Metabolic Rate (BMR), Cardiac Output (C.O) and Body weight (BW).

Various surveys and investigations on the correlations between age and BMR, C.O. and BW have been reported. Significant uncertainty is present in the published results due to various population samples and methods for measurement/estimation have been used. Work done by Aub and Du Bois (1917) on the reduction in BMR of humans as a result of aging has been widely quoted (Bruen, 1930, Henry, 2005 and 2000). In this research, the Dubois normal standards for BMR were used for deriving the average percentage depreciation of BMR with respect to age. Given the median age of 75yrs for the older population, a BMR at 70W was estimated for a typical old person, which equates a 19.2% reduction compared to a typical person represented by the Fiala model. The mean body weight of a typical 75yrs old person was sourced from the data set for the United States 1960-2002 (Ogden, 2004). The resultant value, 66kg, represents 10% reduction compared to the Fiala model. Similarly, the typical basal cardiac output value for the older population was derived from (Brandfonbrener, 1955). These values, as summarized in Table 1, were then imported into the Fiala model where modifications were made for the experiments in the rest of the paper.

Table 1. BMR, C.O. and body weight of a typical person and a typical old person

	Typical person (Fiala model)	Typical old person (75yrs)	Change
BMR (W)	87	70	-19.2%
Cardiac Output (L/min)	4.73	4.05	-14.4%
Body Weight (kg)	73.3	66	-10%

Thermal sensation and local discomfort simulation

Three sets of environmental conditions and corresponding clothing levels (Table 2) were used in this quasi steady-state simulation. The conditions and clothing are chosen to ensure overall neutral thermal sensation for the standard human model. Note that the predicted mean vote (PMV) values calculate with ISO7730 method was on the slightly cool side compared to the prediction from the Fiala model. Each model was subjected to a 180 min exposure to each condition. Data was taken at the end of each experiment. It was anticipated that the model of an older person would show a cooler thermal sensation vote in each case compared to the standard model.

Table 2. Test conditions and details of clothing insulation for the "neutral" states

Condition	Ambient temp.	Other parameters	Clothing details	ISO7730 PMV
24°C, 0.6clo	23.8°C	MRT = Ta Va = 0.1 m/s RH = 40% Act = 1.1 met	Shirt, briefs, trousers, socks, street shoes (0.62 clo)	-0.3
21°C, 0.9clo	21.0°C		Shirt, briefs, trousers, socks, street shoes, sweater (0.92clo)	-0.5
18°C, 1.3clo	18.5°C		Under shirt, shirt, briefs, trousers, socks, warm shoes, outdoor jacket (1.35clo)	-0.4

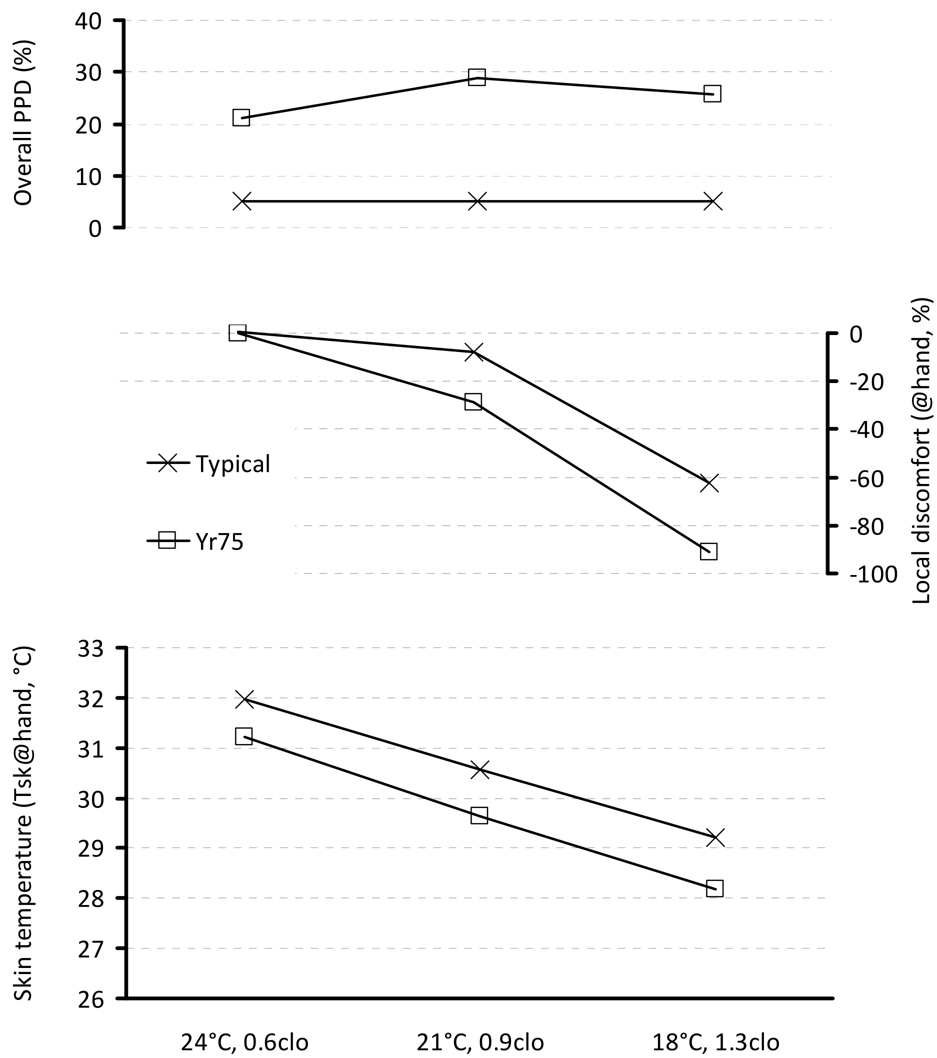

Figure 4. PPD, local discomfort and hand skin temperature

Figure 4 shows the simulation results from the experiments. As anticipated, the overall PPD predicted by the standard model was close to minimum in all cases, whereas the model of an older person demonstrates cool sensation with a PPD in the region of 20-30%. Significant differences were observed in local discomfort, where the older person shows much higher local (at hands, where skin is exposed) discomfort than that of the standard model. This may be attributed to the combined effect of lower metabolic rate, reduced blood circulation to the extremities, and lower heat capacity of the body parts due to the loss of weight. The skin temperature at hands as shown in the chart decreases with ambient temperature, whereas the difference between the standard model and the model of an older person widens. These results were consistent with findings from the literature that older people were more prone to cold discomfort at extremities.

Transient simulation of cooling and re-warming

A transient simulation was carried out using the original Fiala model and the model of an older personal to compare the dynamic responses to the changing thermal environment. The experiment was designed to represent a scenario that could happen in everyday life. A person wearing shirt and trousers (0.6clo) stays in a comfortable room (Ta=24°C) for 60min before move to a cooler room at 18°C. After 60 minutes in the cooler room, the person puts on a warm jacket (total insulation 1.35clo), and remains for a further 60 minutes. He then moves back to the comfortable room without taking off the jacket and remains there for another 60 minutes. Other parameters of the experimental condition include MRT = Ta, Va = 0.1 m/s, RH = 40%, and Act = 1.1 met. Note that 24°C/0.6clo and 18°C/1.35clo would both be evaluated as thermal neutral conditions in a quasi steady-state simulation.

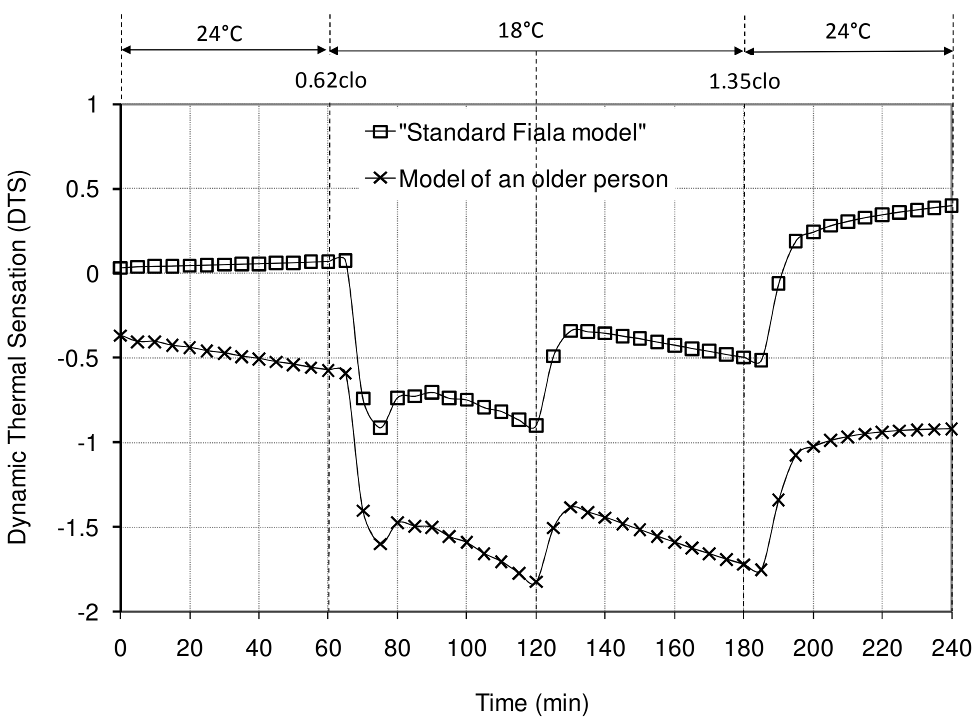

Figure 5. Thermal response and sensation in transient conditions

Figure 5 shows the results from transient simulations. If a typical person as the standard Fiala model represented participated in the experiment, he would experience neutral thermal sensation during the first hour. In the cool room during the second hour, his thermal sensation would be cool (~ -1 DTS). Putting on a warm jacket would bring him back to the comfort zone (-0.5~0.5 DTS). When the person went back to the comfortable room without taking off the jacket, his thermal sensation would move to the warm side of the scale.

However, if the person who participated in the experiment was old (e.g. at 75yrs of age), this was what would happen: he would feel slightly cool in the comfortable room, and significantly cooler in the cool room. Putting on a jacket would only stop the thermal sensation dropping further. Even after he moved, back to the comfortable room with the warm jacket on, it would not bring his thermal comfort to the level when the experiment started. The implication of this result is that due to (primarily) the reduced metabolism, an old person would feel colder in an environment compared to a typical person. Conventional interventions such as putting on more cloths has only limited effect, as the body would not be able to generate enough heat to re-warm it quickly. For the similar reason, it would take the aged body considerably longer to restore its original thermal state at the start of the experiment, even after being moved to the thermally warm environment. This experiment highlighted the significance of the historical thermal state of the body when non-steady state thermal comfort is considered.

Conclusion

The new regime of low energy building design and the exploitation of the adaptive comfort strategies require a new way to evaluate thermal comfort for specific user groups of the indoor environments. The traditional steady-state metrics such as PMV may not be suitable for this purpose. It is anticipated that dynamic thermal comfort models based on human thermo physics and physiology will find more applications in building design and operation. On the other hand, the existing human models are based on a so-called "typical" person, which unnecessarily represents the characteristics (therefore thermal comfort requirement) of a particular user group.

The human body changes with aging. Large body of research has found clear correlations between age and body composition, regulatory functions and other basic physiological parameters. How these changes will effect the thermal comfort requirement of an aged person has not been thoroughly investigated. This paper started with collecting information on age related reduction in BMR, Cardiac Output (C.O.) and Body Weight (BW) from the literature, to build a new model based on the existing Fiala model. Sensitivity test on these factors has shown that the BMR is the main contributor to the changes in thermal comfort requirement, e.g. thermal neutral temperature and thermal sensations. We also carried out quasi steady-state simulation to compare the thermal comfort level in the typical person (existing Fiala model) and the typical older person (the new model) under the same environmental conditions. It was found, as expected, that the older person would feel cooler than the typical person would, due to the reduced metabolism. Also significantly is the worsened local comfort at the exposed skin areas (e.g. hands) in the older person, as a result of combined effect of reduction in BMR, C.O. and BW.

A transient simulation was also carried out to demonstrate the dynamic interaction between the environment and thermal comfort. The experiment showed that the history of the thermal state of the body plays an important role in the thermal sensations that a person is experiencing presently. Especially for the older person, excessive exposure to a cold environment may lead to overcooling of the body, which cannot be rectified by putting on warm clothes. Even after moving back to a warmer environment, the older body would take much longer to recover to its original thermal state. The scenario and the simulation result are both plausible, although experimental data may be required to serve as validation of the new model.

This study is an early attempt to use detailed human models to study the implications of aging on thermal comfort requirements. It is assumed that the Fiala model remains valid after changes have been imposed on the parameters including BMR, C.O. and BW. Many other aspects of aging has not been considered in the present work, including the changes in body composition (e.g. fat content and distribution, muscle mass, total body fluid, and blood capacity) and thermoregulatory functions (e.g. sensory, vasoconstriction/dilation, shivering and sweating functions, and Q10 effect). The impact of these factors, and the validation of the resultant model, will be further investigated in future studies.

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