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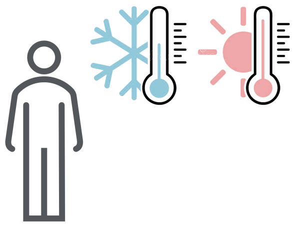
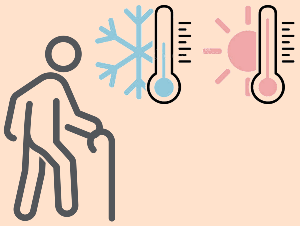
Predicting Elderly Thermal Sensation

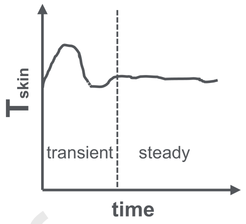
A thermal sensation model for the older population can assist in the development of products that achieve thermal comfort needs of this age group



Thermal sensation models in literature are derived from non-elderly physiological and subjective data



An elderly thermal sensation model was developed from elderly experiments published in literature with the aid of an elderly bioheat model



The developed model predicts elderly thermal sensation under steady and transient conditions

A thermal sensation model for elderly under steady and transient uniform conditions

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Abstract

Sub-optimal thermal conditions influence the health and well-being of elderly people and deteriorate their cognitive functions due to age-induced changes in thermoregulatory mechanisms. Addressing the thermal comfort needs of elderly is better aided when a robust predictive thermal sensation (TS) model exists. However, available TS models in the literature are based on physiological and subjective data collected from young subjects, and their use to assess elderly TS is inappropriate.

In this work, a model for predicting elderly TS under steady and transient states was developed from published experimental data under controlled environment. The model predicts the mean TS of elderly people in terms of their average skin temperature, rate of change of skin temperature and core temperature. The model was coupled with a robust elderly bioheat model, enabling the prediction of elderly TS from environmental conditions. The TS model was further extended with a correlation that links the required physiological data for sensation prediction with few segmental skin temperatures that can be measured to enable the development of TS monitoring devices for the elderly. The model and the approach of using segmental temperatures in TS prediction were validated using different experimental measurements and subjective data than those used in the model development. Good agreement between experimental and predicted TS was achieved under varying steady and transient environments. The model predicts the elderly TS in ambient temperatures ranging from 13 °C to 43 °C and in transient settings with up to a 10 °C step rise or drop in ambient temperature.

Keywords: Elderly thermal sensation; elderly thermal comfort; elderly thermoregulation; transient thermal sensation model.

Highlights

- Models for young adults are inadequate for predicting elderly thermal sensation
- An elderly thermal sensation model was derived from published experimental data
- TS model was validated with other published data for steady & transient conditions
- TS model applies to ambient range of 13 °C to 43 °C and to step changes up to 10 °C
- A correlation was developed to predict elderly TS from segmental temperatures

Nomenclature

a_i	Coefficient "i" for the elderly TS model [-]
I_{clo}	Clothing insulation [clo]
MET	Metabolic rate [met]
MRT	Mean radiant temperature [°C]
RH	Ambient air relative humidity [%]
T_{amb}	Ambient air temperature [°C]
TS	Thermal sensation [-]
TSV	Thermal sensation vote [-]
TS_0	Steady component of thermal sensation [-]
$T_{sk,av}$	Skin average temperature [°C]
$T_{sk,av,n}$	Skin average temperature at thermoneutrality [°C]
$T_{sk,i}$	Skin outer temperature of segment " i " [°C]
T_{cr}	Core temperature [°C]
$T_{cr,n}$	Core temperature at thermoneutrality [°C]
$T_{cr,i}$	Core temperature of segment " i " [°C]
$\frac{dT_{sk,av}}{dt}$	Rate of change of skin average temperature [$^\circ C/min$]
$\Delta T_{sk,av}$	Skin temperature deviation from thermoneutrality [°C]
ΔT_{cr}	Core temperature deviation from thermoneutrality [°C]
V_{air}	Background air velocity [m/s]

Subscripts

exp	experimental
cr	Core
$cr, bioheat$	Core predicted by bioheat model
cr, est	Core estimated
cr, i	Core Segment " i "
cr, n	Core thermoneutral
sk	Skin
sk, av	Skin average
sk, av, n	Skin average thermoneutral
sk, av, est	Skin average estimated
$sk, av, bioheat$	Skin average predicted by bioheat model
sk, i	Skin Segment " i "

1. Introduction

Thermal sensation (TS) models are necessary for people of all ages, despite that the incentives behind having such models may differ by age group. Young TS is usually assessed to examine the influence of the surrounding thermal environment on workers' productivity [1, 2], to minimize the energy consumption of air conditioning systems [3, 4], or to investigate the effect of specific thermal environments on thermal comfort [5-7]. Meanwhile, and in light of climate change [8], key drivers behind the assessment of elderly TS are concerns related to health and well-being of the elderly [9, 10], allowable temperature drifts for efficient air conditioning systems [11], and cognitive function deterioration attributed to suboptimal TS [12]. Elderly people in unregulated thermal environments are particularly vulnerable to the effects of global warming and extreme weather due to impaired body thermoregulation [13-15], which puts them at risk of hypothermia and hyperthermia. The risk is escalated when the outdoor weather gets more severe due to an event such as heat waves [16, 17] or a phenomenon such as the urban heat island effect [18, 19]. With the increased morbidity and mortality in the aged population due to extreme weather [16, 17], and given that the average age of the world's population increasing at unprecedented rate [20, 21], it is evident that addressing the thermal comfort needs of older individuals is essential.

The thermoregulatory mechanisms of the human body naturally decline with aging, becoming less responsive to cold and hot stimuli [22, 23]. The physiological changes causing this decline include: decreased basal metabolic rate and cardiac output, decreased dilated skin blood flow, increased constricted skin blood flow, reduced sweat volume, delayed vasoconstriction, delayed vasodilation, delayed sweating, and altered body fat distribution with increased fat thickness in the abdomen region [22, 23]. Furthermore, while some studies indicate no significant variations in TS between the two age groups [24-27], there is strong evidence in the literature for the following differences:

i) Thermal sensitivity drops progressively with aging where the ability to perceive warm stimuli diminishes more pronouncedly than the ability to perceive cold stimuli [28-30];

ii) The decline in thermal sensitivity seems to be non-uniform across different body parts, with the maximum decline happening at extremities [28]; and

iii) Older subjects prefer warmer environments than younger counterparts [11, 31, 32].

Elderly preference of warmer thermal environments can be mainly attributed to the reduced metabolic heat production [33, 34]. Nonetheless, the question about the physiological basis of the reduced thermal sensitivity received more than an answer in the literature. Slava and André [28] have summarized the possible underlying mechanisms for the reduced elderly thermal sensitivity into three:

i) **The reduction of sensory intraepidermal nerve fibres' density:** Researchers have confirmed a significant reduction of sensory nerve fibres [35-37], which may account for age-related decline in thermal sensitivity [28].

ii) **The impaired nerve fibres' functioning due to diminished vascular network:** Assuming that the anatomical structures responsible for thermal sensation are relatively preserved in older people, the decreased vascular supply to skin may have an impact on those structures' functional characteristics [38].

iii) **The age-related changes in the peripheral nervous system in the old**: Assuming that the process of coding sensory stimuli into action potentials is relatively well preserved, the transmission properties of peripheral nerve system might be affected by age-related structural and functional changes [39].

The differences between the two age groups in terms of thermoregulation and thermal sensitivity imply that the TS models generated from young subjective data cannot be utilized to predict elderly TS; an elderly TS model is thus required. The model must be able to predict elderly TS under transient conditions because humans, young and old, often encounter transient thermal environments while going about their everyday activities. Moving from an outdoor hot environment into an air-conditioned mall or from an air-conditioned residence into the outdoors are clear examples of routine daily activities that represent an abrupt change in the thermal environment. Moreover, interventions that focus on optimizing thermal comfort sometimes depend on transient effects, such as the use of intermittent flows to improve comfort at low energy cost [40, 41]. As a result, a reliable tool to assess the comfort needs of elderly shouldn't be limited to steady conditions.

TS at steady state is defined by a static signal delivered to the brain by peripheral and central thermoreceptors for the skin and core temperatures, respectively [42, 43]. At transient conditions, however, TS is defined by that same static signal in addition to a dynamic signal that that is based on the rate of change of core and skin temperatures [42, 43]. Therefore, different thermoreceptors' responses to different thermal environments should be considered for developing a TS model. *Hensel* [43] is among the first who proposed that human TS can be expressed as a function of skin temperature ($\mathrm{T_{sk}}$) and its rate of change $\left(\frac{\mathrm{dT_{sk}}}{\mathrm{dt}}\right)$ as well as the area of stimulation. *de Dear et al.* [44] then developed a skin receptor impulse frequency model in which the receptor response is divided into a static component proportional to $\mathrm{T_{sk}}$ and a dynamic component proportional to $\frac{\mathrm{dT_{sk}}}{\mathrm{dt}}$; non-uniform thermal sensitivity of body parts was accounted for by assigning different sensation “area summation factors”. *Taniguchi et al.* [45] developed a correlation that links the overall body TS to the average facial T_{sk} and its rate of change in vehicle environments when a limited number of body parts was exposed to transient conditions. Wang [46] developed a dynamic TS model that has two components: a static component derived from Fanger’s predicted mean vote model, and a dynamic component based on the rate of heat storage in the body as predicted by a bioheat model. *Fiala* [47] developed dynamic TS model by retrieving large dataset for subjective TS from experiments in the literature and correlating them to predicted physiological parameters predicted by a bioheat model. The TS in his model at transient state depends on the mean skin temperature ($T_{sk,av}$), the rate of change of mean skin temperature $\left(\frac{dT_{sk,av}}{dt}\right)$, and the hypothalamic temperature. *Guan* [48] developed a transient TS model for vehicle environments based on the T_{sk} and the rate of heat gain of the body predicted by a bioheat model. *Zhang* [42] developed a transient TS model for complex non-unform thermal environment that predicts local and overall TS based on local T_{sk} and $\frac{dT_{sk}}{dt}$ as well as the rate of change of core temperature. *Schellen et al.* [49] developed a TS mathematical model based on neurophysiology where TS is a function of neurons discharge rate obtained from local T_{sk} and T_{cr}. All the described models, however, are based on subjective and physiological data from non-elderly subjects and cannot be used to predict elderly TS due to the discrepancies outlined above.

There have been few recent studies that investigated elderly TS in the literature. For example, *Xiong et al.* conducted a controlled climate chamber experiment on 16 older people who were exposed to four different ambient temperatures (T_{amb}) [30]. Based on the data collected, correlations for TS and comfort with operative temperature and TS with $T_{sk,av}$ were provided. However, TS votes were gathered at a steady state, the exposure settings were limited [30]. *Wang et al.* investigated the transient physiological and subjective responses of older people when they were exposed to a step-rise or step-drop in $\mathrm{T_{amb}}$ starting from neutrality and when they were returned to neutral ambient conditions [50]. The study provided mathematical relations linking TS to $\mathrm{T_{sk}}$ and $\frac{\mathrm{dT_{sk}}}{\mathrm{dt}}$. The experiment did not include steady exposure conditions other than neutrality (i.e., hot and cold exposures) which limits the range of applicability of such relations. Additionally, $\mathrm{T_{sk}}$and $\frac{\mathrm{dT_{sk}}}{\mathrm{dt}}$ are insufficient to predict TS under all circumstances, such as when the body stores heat and is later exposed to a new environment; under such conditions, $\mathrm{T_{cr}}$ plays a critical role in defining the TS. In summary, the detailed physiological-based TS models in literature are based on young-participants data whereas the elderly TS correlations have limited applicability and uncertain generalization performance. To the best of the authors' knowledge, there has been no TS model for the elderly population that can predict their TS under different steady and transient conditions in terms of physiological parameters.

The aim of this work is to develop a robust elderly TS model based on subjective votes from published climatic chamber experiments in the literature. The model predicts TS of elderly under steady and transient conditions from physiological parameters such as skin and core temperatures and the rate of change of skin temperature. Some studies provide the subjective responses of the elderly to the thermal environment without providing their physiological responses. The physiological response in such experiments is predicted via the robust bioheat model of *Rida et al.* [22]. Hence, the elderly bioheat model is used to develop a correlation between the required inputs of the established sensation model and segmental skin temperatures that can be measured non-invasively during regular activities of the elderly. The correlation enables real-time prediction of elderly TS using few segmental temperatures, making it suitable for the development of elderly TS monitoring devices that ensure their comfort needs are met and associated health risks are reduced.

2. Materials and Method

The elderly TS model was developed in this work by correlating subjective responses of elderly subjects from multiple independent experiments existing in the literature with physiological parameters such as skin and core temperatures. In studies where only the subjective responses to the thermal environment of the experiment are provided, the associated physiological responses of subjects are obtained from the robust elderly bioheat model of *Rida et al.* [22]. The predicted responses are then used in developing the TS model as shown in the flowchart of **Figure 1**. The model of *Rida et al.* is a transient multi-segment multi-node bioheat model that incorporates the physiological changes that occur to humans with aging based on literature experiments. The model, accounts for the decreased metabolic rate, the change in fat thickness in body segments, and the attenuated and delayed vasoconstriction, vasodilation, and sweating responses [22]. One of the main features of *Rida et al.* model is including a coupled blood circulation model that solves for blood flow based on the cardiac output and the peripheral blood flow while accounting for arterial and venous circulations, arteriovenous anastomoses mechanism, and skin perfusion. The model was validated with elderly experimental data spanning a wide range of ambient conditions [22].

Within the context of this study, we refer to elderly as individuals who are over the age of 60, as defined by the United Nations [51]. Experimental data used to develop the model was confined to climatic chamber experiments since they are more controlled than field experiments and can lead to a more accurate model. Because the model is intended to predict the TS of healthy individuals, the data utilized in developing and validating the model was limited to data of healthy older adults. Exercise attendance and the willingness to engage in exercise decrease as people become older, according to a survey of almost 92,000 adults in England [52]. As a result, the retrieved data for use in the TS model was restricted to data for elderly people engaging in sedentary activities such as sitting, watching television, etc. Prior to the development of the model, the collected subjective data, as well as the measured or predicted physiological data were split into training and testing sets to enable the model to be evaluated using previously unseen experimental data. The validation data set was ensured to include a wide range of TS and a good sample size. Some transient experiments featured successive votes on TS immediately following a step change in environmental variables; they are appropriate to be used in the development phase of the mode than in its validation, thus they were retained for modeling.

The steady and transient experiments used to develop and validate the TS model are summarized in the subsection that follows. Then the modelling method for the steady component of TS is then presented, followed by the modelling approach for the transient component of TS. The following are included in the modelling part: assuming an appropriate profile for TS function, selecting suitable predictors for TS at steady state and at different transient situations, selecting a profile for thermal sensation dependency on each predictor, and means of regression analysis. Then, the validation approach of the developed TS model is presented. Finally, a brief explanation of the established correlation that allows predicting TS from a few segmental temperatures is provided, and the reader is referred to **Appendix A** for further information on the correlation's development and validation.

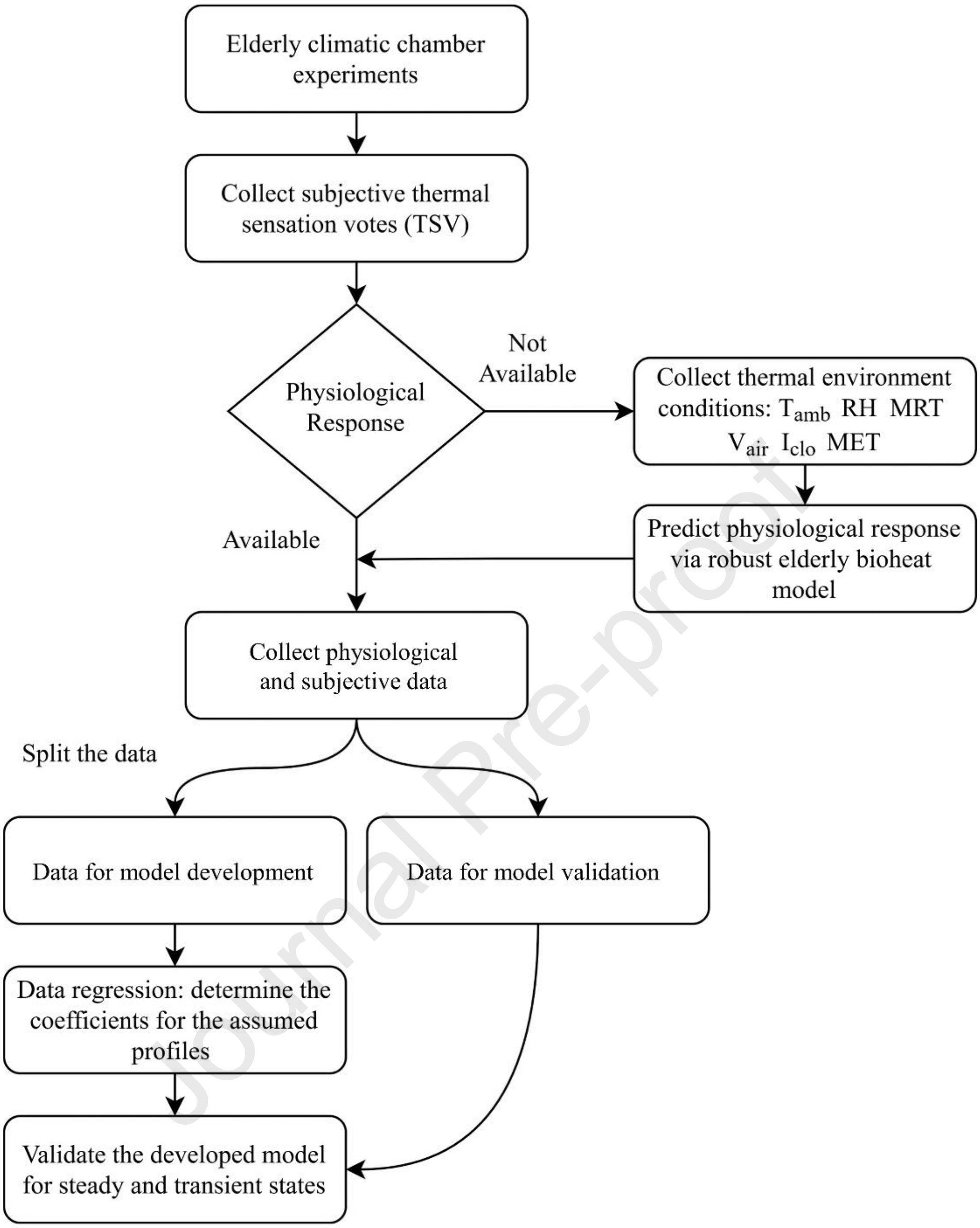

Figure 1 Flowchart of the methods used to establish an older TS model based on climatic chamber experiments available in the literature

2.1.Published experiments used in the development of the TS model

The literature was searched for studies in which older persons were subjected to steady and transient environmental conditions while collecting their thermal sensation votes (TSV) on the associated thermal environment.

2.1.1. Published experiments used in the development and validation of steady component of the TS elderly model

The steady component of the TS model was developed using 690 votes from 6 independent studies and 16 distinct experiments. Since the model is intended to predict the mean elderly TS, the mean votes from different experiments are used to develop the model. The number of subjects in each experiment ranges between 8 [53] and 109 [29]. The average age of subjects within each experiment was at least 65 years [53]. The experiments included semi-nude [54] subjects and subjects with clothing insulation up to 1.06 clo [55]. The subjective data utilized in the development of the steady component of the TS model spans a large spectrum of neutral, warm, and cold TS. One set of experiments [55] was preserved to validate the prediction of the TS model under different steady conditions. The experiments utilized in the development and validation of the steady TS component are listed in **Table 1**.

Table 1 Published experiments used in the development and validation of the steady component of the TS model. Experiment of *Soebarto et al.* [55] was used for validation, others were used for development

Experiment	**Year of Study**	**Number of Subjects**	**Age of Subjects**	**T_{amb} [°C]**	**I_{clo} [clo]**	**Physiological response**	**Study Summary**
Tsuzuki and Ohfuku **[29]**	2002	109	72.4 ± 5.3	23, 27, 31	0.63	Measured	Investigated the thermal comfort needs of elderly people compared to college-age people under different climatic chamber conditions
Tsuzuki and Ohfuku **[29]**	2002	109	72.4 ± 5.3	25, 29	0.63	Bioheat*	
Xiong et al. **[30]**	2019	16	70 ± 5	21, 25, 28, 31	0.55	Measured	Studied the physiological (skin temperature, electrocardiograph) and psychological (thermal comfort, sensation) responses of elderly subjects to different thermal settings.
Dofour and Candas **[54]**	2007	15	67.8 ± 3.7	28, 40	0.04	Bioheat*	Studied the effect of aging on humans' thermal responses (sweating and sensory aspects) during passive heat exposure
Wu et al. **[53]**	2019	8	65 ± 3	18, 26, 34	0.5	Measured	Examined psychological, behavioural, and physiological responses of elderly at different ambient conditions
Wang et al. **[50]**	2019	18	67.5 ± 4.8	26	0.5	Measured	Studied the responses of Chinese older subjects to moderate cold and warm temperature steps
Tochihara et al. **[56]**	2021	9	69.6 ± 3.2	28	0.1	Measured	Aimed to determine age-related differences in thermoregulatory, cardiovascular, and sensory responses to a wide range of ambient temperatures
Soebarto et al. **[55]**	2019	22	68.8 ± 3.7	20, 25	0.72/1.06	Measured	Investigated whether older people had different thermal sensations, comfort, acceptability, and preferences from their younger counterparts when exposed to the same conditions

** Bioheat: predicted via the elderly bioheat model*

2.1.2. Published experiments used in the development and validation of the transient component of the TS elderly model

Published experiments used in the development of the transient term of the TS model included the following scenarios: step rise/drop in $\mathrm{T_{amb}}$ starting from neutral conditions; step rise/drop in $\mathrm{T_{amb}}$ starting from non-neutral conditions; and gradual rise/drop in $\mathrm{T_{amb}}$. Multiple votes were gathered successively from subjects when exposed to the new environment in the step-change experiments [50], which facilitates the process of deriving the transient term of the TS model. The gradual-change experiment [56] used in the development of the model involved five stages: steady under neutral temperature (30 minutes at 27 °C), gradual warming (28 °C to 43 °C in 30 minutes), gradual cooling (43°C to 13 °C in 60 minutes), gradual rewarming (13 °C to 26 °C in 30 minutes), and steady under neutral temperature (30 minutes at 27 °C). TS votes were gathered throughout all stages. The rate of change of $\mathrm{T_{amb}}$ was 0.5 $°\mathrm{C.min^{-1}}$ for both the warming and cooling phases. The maximum $\mathrm{T_{amb}}$ reached in the experiment was 43 °C and the minimum was 13 °C. The experiments used in the development of the TS model cover a wide range of possible transient scenarios an elderly subject may experience. A set of experiments [57] was retained to validate the TS model prediction under different transient scenarios. The experiments utilized in model development and validation are summarized in **Table 2**.

Table 2 Published transient experiments used in the development and validation of the transient term in the TS model. Experiment of *Tochihara et al.* [34] was used for validation, others were used for development.

Experiment	**Year of Study**	**Number of Subjects**	**Age of Subjects**	**T_{amb} [°C]**	**I_{clo} [clo]**	**Type**	**Physiological response**
Wang et al. [50]	2019	18	67.5 ± 4.8	26-21-26 26-23-26 26-29-26 26-32-26	0.5	Step change in T_{amb}	$T_{sk,av}$: Measured T_{cr}: Bioheat*
Tochihara et al. [56]	2021	9	69.6 ± 3.2	28-43-13-28	0.1	Gradual change in T_{amb}	$T_{sk,av}$: Measured T_{cr}: Bioheat*
Wu et al. [53]	2019	8	65 ± 3	26-18 26-34	0.5	Step change in T_{amb}	$T_{sk,av}$: Measured T_{cr}: Bioheat*
Tochihara et al. [57]	1993	10	72 ± 1.4	25-15-25 25-35-25	0.63	Step change in T_{amb}	$T_{sk,av}$: Bioheat* T_{cr}: Bioheat*

** Bioheat: predicted via the elderly bioheat model*

2.2.Thermal sensation model for elderly people

The human body senses heat and cold through a network of peripheral and internal thermoreceptors located below the surface of the skin. As a result, the body can only indirectly sense T_{amb} by sensing the temperature of skin-level nerve endings. The temperature and its rate of change are both perceived by thermoreceptors [58]. Internal thermoreceptors enable the body to sense its core temperature (T_{cr}). They significantly affect TS in situations involving activity and in particular transient occurrences such as when the body accumulates heat and then is exposed to a new environment. Since the signals of peripheral and central thermoreceptors constitute the physiological origins for human TS [58], the age-affected response of such thermoreceptors is the core element of the TS model developed in this work.

The response of thermoreceptors can be static or dynamic [43]. In young TS models, TS is usually expressed as a function of a steady component and a dynamic component that arises under non-steady conditions [42, 46, 47]. Adopting this approach, the TS of an older individual may be expressed as follows:

$$\mathrm{TS} = f\ (\mathrm{TS}_0 + \Delta\mathrm{TS}) \qquad \textbf{(1)}$$

where

TS_0 = Steady component of thermal sensation

$\Delta\mathrm{TS}$ = Transient component of thermal sensation

The TS model is intended to be predicted on a 7-point ASHRAE scale; thus, the output should be limited between -3 and 3. As proposed by *Fiala* [47], an assumed profile for TS was a hyperbolic tangent function. **Equation (1)** becomes

$$\mathrm{TS} = 3\tanh\,(\mathrm{TS}_0 + \Delta\mathrm{TS}) \qquad \textbf{(2)}$$

2.2.1. Steady TS modeling

Under steady environmental conditions, TS is primarily defined by signals from cold and warm peripheral thermoreceptors, which justifies being predictable from skin temperature only in young models [42, 46, 47, 59]. Warm and cold sensations of the environment are perceived via different peripheral thermoreceptors [60]. The number of cold receptors in the body is significantly higher than the number of warm receptors [61]. Additionally, thermoreceptor of the two classes are not situated at the same depth from the outer skin layer; warm receptors are found in deeper skin layers on average [60]. The variations in type, distribution density, and depth from the outer skin layer between cold and warm thermoreceptors suggest that the warm and cold sensations do not share the same dependency on skin temperature [60]. Thus, TS_0 is expressed as a function of the deviation of $\mathrm{T}_{\mathrm{sk,av}}$ from the thermoneutral mean skin temperature $\left(\mathrm{T}_{\mathrm{sk,av,n}}\right)$ of elderly, where positive and negative deviations are treated separately. The equation of *"Hardy and DuBois"* [62] is used to define $\mathrm{T}_{\mathrm{sk,av}}$:

$$\mathrm{T_{sk,av}} = 0.07\,\mathrm{T_{sk,forehead}} + 0.14\,\mathrm{T_{sk,arm}} + 0.05\,\mathrm{T_{sk,hand}} + 0.07\,\mathrm{T_{sk,foot}} + 0.13\,\mathrm{T_{sk,calf}} + 0.19\,\mathrm{T_{sk,thigh}} + 0.35\,\mathrm{T_{sk,trunk}} \quad \textbf{(3)}$$

The thermoneutral mean skin temperature $\mathrm{T_{sk,av,n}}$ is the mean skin temperature $\mathrm{T_{sk,av}}$ when the TSV of subjects is "neutral" (i.e., TSV=0). Due to individual differences between subjects, $\mathrm{T_{sk,av,n}}$ was set to the average $\mathrm{T_{sk,av,n}}$ of the studies of *Dofour and Candas* [54], *Wang et al.* [50], and *Tochihara et al.* [56] which was found to be $\mathrm{T_{sk,av,n}} = 33.33\ \mathrm{°C}$.

Since the TSV from the considered experiments were all obtained at steady state, the term ΔTS in **Equation (2)** can be ignored. Similar to young TS models [47], a linear relationship between the steady component $\mathrm{TS_0}$ and the deviation of $\mathrm{T_{sk,av}}$ from its neutral value was adequate to reproduce the experimental TS data. The intercept of the function is set to zero to ensure a neutral sensation at thermoneutral skin temperature. Expressing $\mathrm{TS_0}$ as a function of $\mathrm{T_{sk,av}}$ deviation from $\mathrm{T_{sk,av,n}}$, **Equation (2)** becomes

$$\mathrm{TS} = 3\tanh\left(\mathrm{a_0}\left(\mathrm{T_{sk,av}} - \mathrm{T_{sk,av,n}}\right)\right) \quad \textbf{(4)}$$

Using the *"Levenberg–Marquardt"* algorithm [63], the coefficient "$\mathrm{a_0}$" -that represents the sensitivity of elderly TS to skin temperature deviation from neutrality- is found for cold and warm stimuli from cold and warm steady experiments, respectively.

2.2.2. Transient TS modeling

For a person not doing exercise, transience is initiated by changes in his/her thermal environment. Under transient conditions, the TS is generally different from what the steady TS model predicts for young and elderly. Examining the literature and analyzing transient elderly experiments reveal two major sources of divergence from steady TS: i) the influence of the rate of change of skin temperature, and ii) the influence of the core temperature. In some young TS models, the rate of change of skin temperature and the core temperature or its rate of change are therefore employed as predictors for the transient influence on TS [42, 47].

It is well established in the literature that the rate of change of skin temperature for young affects the discharge rate of thermoreceptors [44, 49, 58], which is the physiological basis for TS dependence on the rate of change of skin temperature. The influence of core temperature on TS, on the other hand, has been found to be significant for exercising subjects and subjects in conditions where the body accumulates heat [47, 64]. The two effects may arise together, but in certain situations only one of them may be significant. For example, the TS of a person suddenly exposed to a very cold environment starting from steady neutral conditions is highly dependent on the rate of change of the skin temperature. In this scenario, the core temperature does not vary significantly in the first few minutes of exposure, and its effect on TS is minimal. The term $\Delta\mathrm{TS}$ in **Equation (2)** is thus decomposed into two terms: $\Delta\mathrm{TS}_{\mathrm{dT_{sk}}}$to account for the effect of skin temperature rate of change; and $\Delta\mathrm{TS}_{\mathrm{cr}}$ to accounts for the effect of core temperature change. Decomposing $\Delta\mathrm{TS}$, **Equation (2)** becomes:

$$\mathrm{TS} = 3\tanh\left(\mathrm{TS}_0 + \Delta\mathrm{TS}_{\mathrm{dT_{sk}}} + \Delta\mathrm{TS}_{\mathrm{cr}}\right) \qquad \textbf{(5)}$$

To derive expressions for the transient components $\Delta\mathrm{TS}_{\mathrm{dT_{sk}}}$and $\Delta\mathrm{TS}_{\mathrm{cr}}$, the following approach is followed:

- The steady component TS_0 is predicted for transient experiments using the steady model established in Section 2.2.1.
- The discrepancy between the TS predicted by the steady model and the experimental TS ($\mathrm{TS}_{\mathrm{exp}}$) is assumed to be caused by the influence of transience.

Thus, by replacing TS in **Equation (5)** by $\mathrm{TS_{exp}}$, the following equation is used to calculate ΔTS from transient experiments

$$\Delta\mathrm{TS} = \operatorname{arctanh}\left(\frac{\mathrm{TS_{exp}}}{3}\right) - \left[a_0\left(\mathrm{T_{sk,av}} - \mathrm{T_{sk,av,n}}\right)\right] \qquad \textbf{(6)}$$

- Intervals in the transient experiments where the transience effect is caused by the rate of change of skin temperature solely are identified. Experiments in which the body retains heat in a non-neutral thermal environment are then used to examine the influence of core temperature. A suitable profile is assumed for predicting $\Delta\mathrm{TS_{dT_{sk}}}$ and $\Delta\mathrm{TS_{cr}}$ from candidate predictors, followed by coefficients determination.

Peripheral thermoreceptors respond to both temperature and rate of temperature change [58].

The brief period at the onset of exposure to new environments in experiments that start from thermoneutrality are selected to derive a predictor for the term $\Delta\mathrm{TS_{dT_{sk}}}$. The four step-change experiments of *Wang et al.* (26–21 ˚C, 26–23 ˚C, 26–29 ˚C, 26–32 ˚C) [50], the two step-change experiments of *Wu et al.* (26–18 ˚C, 26–34 ˚C) [53] and the first part (28– 43 ˚C) [56] of the gradual-change experiment of *Tochihara et al.* -which all start from thermoneutrality were used in this part (see **Table 2** for more details). In these periods, the difference between the experimental TSV and the steady predicted TS may be attributed only to the influence of skin temperature rate of change. **Equation (6)** is used to calculate $\Delta\mathrm{TS_{dT_{sk}}}$ using six different experimental setups where $\mathrm{T_{amb}}$ rises or drops starting from neutrality. A predictor for $\Delta\mathrm{TS_{dT_{sk}}}$ from $\frac{\mathrm{dT_{sk,av}}}{\mathrm{dt}}$ is then derived. The following linear equation that relates $\frac{\mathrm{dT_{sk,av}}}{\mathrm{dt}}$ to its corresponding influence on TS was found to be sufficient for reproducing the experimental findings during both cold and warm exposures:

$$\Delta TS_{dT_{sk}} = a_1 \frac{dT_{sk,av}}{dt} \quad \textbf{(7)}$$

The coefficient "a_1" that represents the sensitivity of elderly TS to the rate of change of skin temperature is obtained through linear regression for both positive and negative $\frac{dT_{sk,av}}{dt}$.

When moving from a thermoneutral environment, the steady model prediction was close to the transient experimental votes. In contrast, when a person moves from non-thermoneutral conditions, large discrepancies were identified between the experimental and predicted-steady TS. For instance, persons who had been exposed to cold and abruptly shifted into neutral settings reported feeling slightly warm or even warm, despite that their skin temperatures were lower than neutral. This was common in step-change [50, 57] and gradual-change experiments [56]. The discrepancy may be caused primarily by the heat storage effect of the body, which could be captured by the core temperature of the body through internal thermoreceptors that are found in the hypothalamus, the spinal cord, abdominal viscera, and in or near the large veins in the upper abdomen and thorax [42]. No exact information was found regarding the distribution density of internal thermoreceptors, but the hypothalamus is known to contain a significant portion of them [42, 58]. Thus, a representative core temperature is determined using the assumed weights of the following equation:

$$T_{cr} = 0.6\, T_{cr,head} + 0.2\, T_{cr,upper\ trunk} + 0.2\, T_{cr,lower\ trunk} \quad \textbf{(8)}$$

The recovery periods from non-thermoneutral conditions after the skin temperature is stabilized are chosen to derive a predictor for ΔTS_{cr}. No information in the literature was found about the exact dependency of TS on the core temperature. However, because of some interactions between skin and internal thermoreceptor signals, it is demonstrated that the impact of core temperature on TS cannot be modeled using a simple correction term that is added to the steady component of TS [47]. To account for these interactions, $\Delta\mathrm{TS}_{\mathrm{cr}}$ was modeled as a function of both $\mathrm{T}_{\mathrm{sk,av}}$ and T_{cr}. The product of two truncated polynomial functions of $\mathrm{T}_{\mathrm{sk,av}}$ and T_{cr} was reported in some young TS models to be a good profile for modeling the integrated effect of skin and core temperature [47]. Since the profile provided a good fit, it was selected as a profile for $\Delta\mathrm{TS}_{\mathrm{cr}}$. When expanded, the selected profile has the following form:

$$\Delta\mathrm{TS}_{\mathrm{cr}} = \mathrm{a}_2 + \mathrm{a}_3\Delta\mathrm{T}_{\mathrm{sk,av}} + \mathrm{a}_4\Delta\mathrm{T}_{\mathrm{cr}} + \mathrm{a}_5\Delta\mathrm{T}_{\mathrm{cr}}^2 + \mathrm{a}_6\Delta\mathrm{T}_{\mathrm{sk,av}}\Delta\mathrm{T}_{\mathrm{cr}} + \mathrm{a}_7\,\Delta\mathrm{T}_{\mathrm{sk,av}}\Delta\mathrm{T}_{\mathrm{cr}}^2 \qquad \textbf{(9)}$$

where $\Delta\mathrm{T}_{\mathrm{cr}} = \mathrm{T}_{\mathrm{cr}} - \mathrm{T}_{\mathrm{cr,n}}$ and $\Delta\mathrm{T}_{\mathrm{sk,av}} = \mathrm{T}_{\mathrm{sk,av}} - \mathrm{T}_{\mathrm{sk,av,n}}$

The core neutral temperature $(\mathrm{T}_{\mathrm{cr,n}})$ was set to 36.76 ˚C which is T_{cr} predicted by the bioheat for an elderly wearing standard clothing (0.63 clo) under steady $\mathrm{T}_{\mathrm{amb}}$ of 26 ˚C. The influence of core signals should appear in the TS equation only when core temperature has a significant effect on TS. Because the model does not account for the effects of activity, the effect of the core is only included during recovery periods from non-neutral thermal environments. Therefore, the term $\Delta\mathrm{TS}_{\mathrm{cr}}$ arises anytime the skin temperature is warm and a negative rate of change of skin temperature occurs, or when the skin temperature is cold, and a positive rate of change occurs. Using multivariate regression analysis on the recovery part of *Wang et al.* experiment (21–26 ˚C, 23–26 ˚C, 29–26 °C, 32–26 °C) and the recovery parts of *Tochihara et al.* experiment (43–28 ˚C, 13–28˚C), two sets of coefficients $(\mathrm{a}_2 \text{ to } \mathrm{a}_7)$ are derived to account for cold and hot recovery situations (see **Table 2** for more details).

2.3.Validation approach of the TS model prediction

The developed TS model is validated with data, which was not employed in the development phase of the model. Under steady environmental conditions, the TS model was validated under four distinct conditions using subjective and physiological data from the experiment of *Soebarto et al.* [55]. The experiment included 22 elderly participants (age: 65-84 years). The relative humidity and velocity of air in the experiment were 40% and <0.1 m/s, respectively. Subjects' mean vote on TS in the experiment varied from -1.45 to 1.23 on an ASHRAE 7-point scale. Under transient environmental conditions, the TS model was validated with data from the experiments conducted by *Tochihara et al.* [57]. Older persons were subjected to a step change in temperature from neutral ($\mathrm{T_{amb}}$= 25 °C) to hot ($\mathrm{T_{amb}}$= 35 °C) or cold ($\mathrm{T_{amb}}$= 15 °C) for 49 minutes before returning to a thermoneutral $\mathrm{T_{amb}}$ ($\mathrm{T_{amb}}$=25 °C). The subjects were wearing standard clothing ($\mathrm{I_{clo}}$ = 0.63 clo). Air humidity and air velocity were kept at 60% and 0.2 m/s in the experiment. The physiological response in this study was predicted by the elderly bioheat model of *Rida et al.* [22] for the two exposure cases.

2.4.Predicting TS from segmental temperatures

The established TS model predicts the TS of an elderly person under transient settings using two inputs: $\mathrm{T_{sk,av}}$ and $\mathrm{T_{cr}}$. The two parameters can be predicted through the elderly bioheat model of *Rida et al.* [22] given the environmental conditions. However, the two parameters are not practical to be measured in real time during typical old activities. Thus, a correlation was developed to link the inputs of the TS model to measurable segmental skin temperatures that are practical to measure. The elderly bioheat model was used to predict $\mathrm{T_{sk,av}}$, $\mathrm{T_{cr}}$ and skin temperature for different segments $\left(\mathrm{T_{sk,i}}\right)$ under the steady and transient conditions of the seven transient experiments listed in **Table 2**. $\mathrm{T_{sk,av}}$ and $\mathrm{T_{cr}}$ were found to be predictable using chest skin temperature $\left(\mathrm{T_{sk,chest}}\right)$ and the forearm skin temperature $\left(\mathrm{T_{sk,forearm}}\right)$. The product of two truncated polynomials was assumed as a profile for both the estimated mean skin temperature $\left(\mathrm{T_{sk,av,est}}\right)$ and the estimated core temperature $\left(\mathrm{T_{cr,est}}\right)$ as function of $\mathrm{T_{sk,chest}}$ and $\mathrm{T_{sk,forearm}}$. Regression analysis was then used to determine the coefficients $(\mathrm{b_0\ to\ b_3})$ and $(\mathrm{c_0\ to\ c_3})$ of the following assumed polynomial equations:

$$\mathrm{T_{sk,av,est}} = \mathrm{b_0 T_{sk,forearm}} + \mathrm{b_1 T_{sk,chest}} + \mathrm{b_2 T_{sk,forearm} T_{sk,chest}} + \mathrm{b_3} \tag{10}$$

$$\mathrm{T_{cr,est}} = \mathrm{c_0 T_{sk,forearm}} + \mathrm{c_1 T_{sk,chest}} + \mathrm{c_2 T_{sk,forearm} T_{sk,chest}} + \mathrm{c_3} \tag{11}$$

The coefficients $(\mathrm{b_0\ to\ b_3})$ in **Equation 10** and $(\mathrm{c_0\ to\ c_3})$ in **Equation 11** are derived from regression analysis for transient experiments. The approach of predicting TS from segmental temperatures was validated at steady state by comparing TS predicted from measured segmental temperatures to subjective votes under different conditions, and at transient state by comparing TS derived from the bioheat segmental temperatures to subjective votes (not used in regression) under different conditions. More details about the development and the validation of the correlation can be found in **Appendix A.**

3. Results and Discussion

In this section, an expression for the steady component of elderly TS is derived followed by deriving the expression for the transient TS component. Finally, the model is validated under steady and transient settings.

3.1.Steady elderly TS model: deriving an expression for elderly TS_0

Using the *Levenberg–Marquardt* algorithm [63], the coefficient "$\mathrm{a_0}$" is found to be 0.425 $℃^{-1}$ for warm stimuli and 0.275 $℃^{-1}$ for cold stimuli. The values are both less than those derived by *Fiala* for young people (1.026 $℃^{-1}$ for warm and 0.298 $℃^{-1}$ for cold) [47], indicating that sensitivity decreases with age, with warm sensitivity being the most affected. Literature backs up this outcome [28]. **Figure 2** depicts the experimental TS data used in developing the steady model, the curve of the elderly TS model resulting from regression analysis, and the curve of young TS as predicted by Fiala TS model, all as a function of $T_{sk,av} - T_{sk,av,n}$.

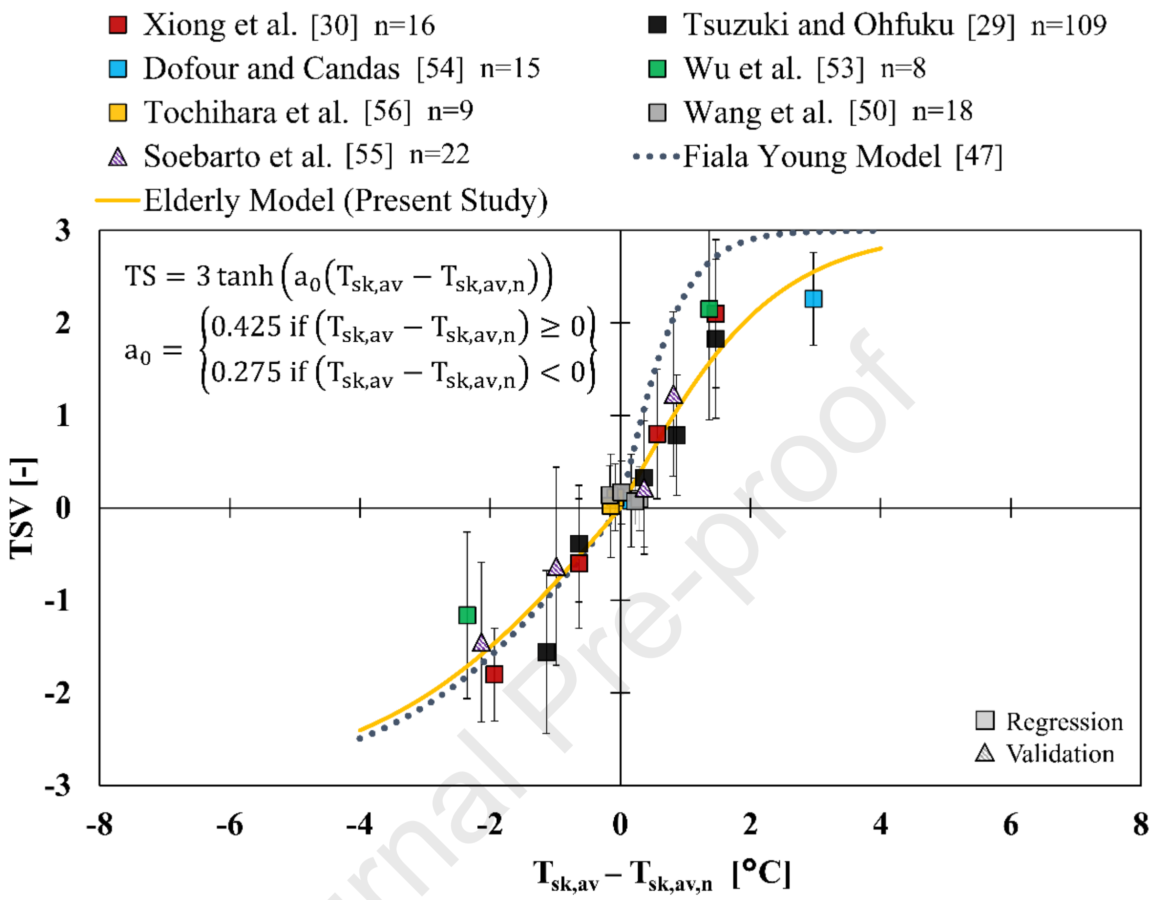

Figure 2 TS of sedentary subjects exposed to a wide range of environmental conditions versus the deviation of their mean skin temperature from neutrality ($T_{sk,av} - T_{sk,av,n}$). *Soebarto et al.* experiment [55] (triangles) was used only for validation. Markers represent means and error bars represent standard deviations

3.2. Transient Elderly TS model: Driving expressions for $\Delta TS_{dT_{sk}}$ and ΔTS_{crsk}

The steady model was used to predict the TS of elderly under transient conditions in the experiments of *Wang et al.* [50] and *Wu et al.* [53]. The experiments included step rises and drops in T_{amb} of 3 °C, 6 °C , and 8 °C. Analyzing elderly transient experiments with small steps in T_{amb} reveals that absolute rates of change of skin temperature that are lower than $0.06\ ^\circ\mathrm{C/min}$ do not cause a significant effect on elderly TS; hence rates of change of skin temperature below this value are neglected.

The coefficient "a_1" obtained through linear regression analysis was **1.6** $\mathrm{min/°C}$ for positive $\frac{dT_{sk,av}}{dt}$ and **0.85** $\mathrm{min/°C}$ for negative $\frac{dT_{sk,av}}{dt}$. **Figure 3** shows TS predicted by the developed TS model corrected by $\frac{dT_{sk,av}}{dt}$ in comparison with experimental TSV. The addition of the rate of skin temperature change to the TS equation resulted in a "steeper" TS response during periods of exposure to a new environment.

In young subjects, the rate of change of skin temperature has a more pronounced impact on TS during transition periods, especially when ambient conditions change rapidly. Young TS in such experiments shows an overshooting behavior [65, 66]. **Figure 3** however shows a smooth transient thermal sensation response without overshooting. This finding is in agreement with elderly experiments that demonstrated a less pronounced effect of $\frac{dT_{sk}}{dt}$ on elderly TS than in young TS, resulting in a gradually changing behavior of elderly TS without overshooting [50] at the moment of the step change in T_{amb}, in contrast to young TS that overshoots [65, 66]. The elderly TS predicted by the model developed in this work was compared to the young TS predicted by Fiala model during a step rise (26-30 ˚C) and decline (26-20 ˚C) in T_{amb}. The TS predicted for older subjects under the same thermal environment was less steep, particularly during the cold exposure [47]. The TS predicted by the Fiala model for young individuals declined from 0.11 to -0.84 after the first 5 minutes of exposure to the cold environment (T_{amb}=20 °C) [47], whereas the TS predicted by the established elderly model dropped from 0.28 to -0.31. Similarly, The TS increased within the first 5 minutes of exposure to the warm environment (T_{amb}=30 °C) from 0.11 to 0.98 [47], compared to a raise from 0.28 to 0.89 predicted by the elderly TS model. This leads to the conclusion that the influence of skin temperature change rate on TS decreases with age.

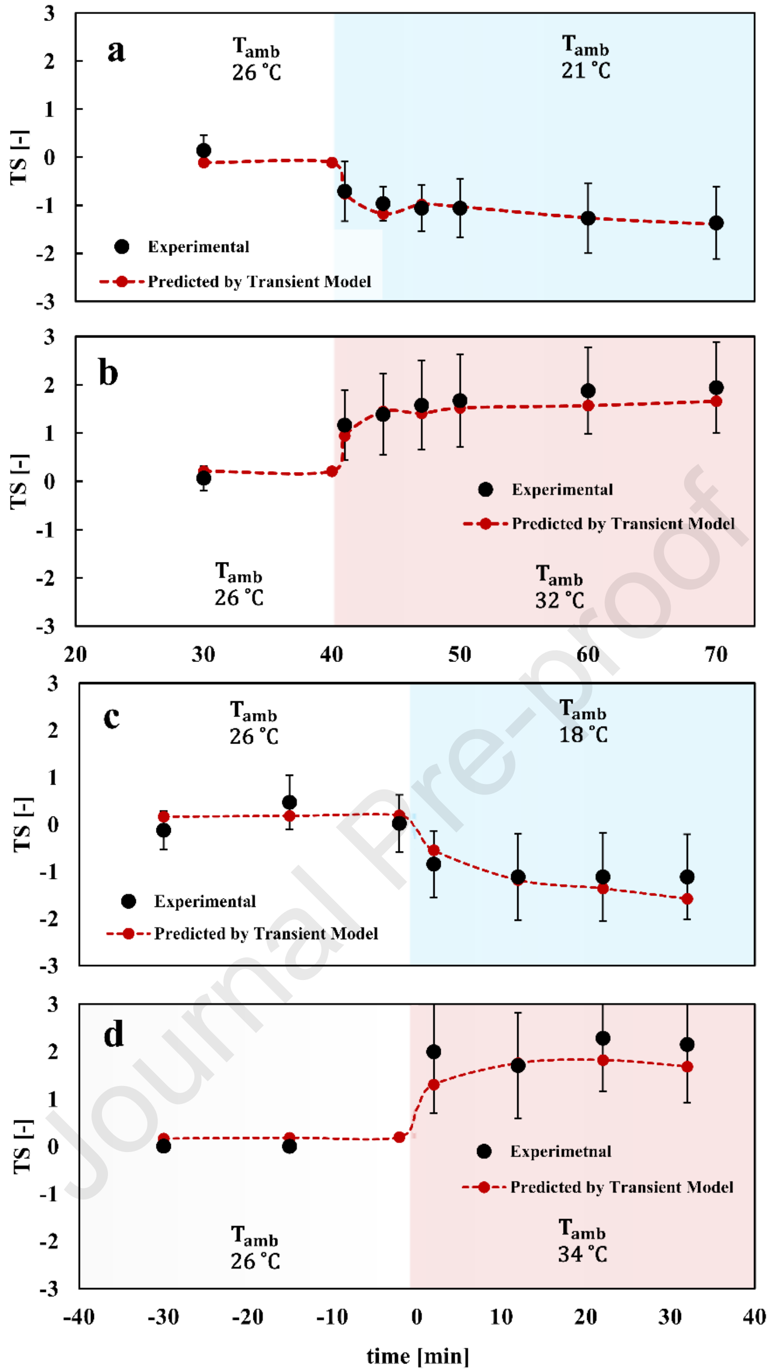

Figure 3 Experimental TS values compared to model predicted TS values (**a-b:** experiment of *Wang et al.* [50]; **c-d:** experiment of *Wu et al.* [53]

The effect of core temperature ΔTS_{cr} was determined from the experiments of *Tochihara et al.* [56] and *Wang et al.* [50] during recovery periods from non-thermoneutral conditions after skin temperature stabilizes. The coefficients

($\mathbf{a_2}$ to $\mathbf{a_7}$) were determined using multivariate regression analysis. The result of the regression analysis is summarized in **Table 3**.

Table 3 Coefficients of ΔTS_{cr} expressed in **equation (9)** obtained by multivariate regression.

Coefficient	**Term**	**Value**	
		$\Delta T_{sk,av} > 0, \frac{dT_{sk,av}}{dt} < 0$	$\Delta T_{sk,av} < 0, \frac{dT_{sk,av}}{dt} > 0$
$\mathbf{a_2}$	**Intercept**	-0.295 [-]	0.260 [-]
$\mathbf{a_3}$	$\Delta T_{sk,av}$	-0.102 [$℃^{-1}$]	-0.267 [$℃^{-1}$]
$\mathbf{a_4}$	ΔT_{cr}	3.220 [$℃^{-1}$]	0.054 [$℃^{-1}$]
$\mathbf{a_5}$	ΔT_{cr}^2	9.827 [$℃^{-2}$]	-7.009 [$℃^{-2}$]
$\mathbf{a_6}$	$\Delta T_{sk,av}\Delta T_{cr}$	31.167 [$℃^{-2}$]	25.003 [$℃^{-2}$]
$\mathbf{a_7}$	$\Delta T_{sk,av}\Delta T_{cr}^2$	-5.276 [$℃^{-3}$]	0.005 [$℃^{-3}$]

The prediction of elderly TS using the derived model is compared to the experimental TSV in the experiments of *Wang et al.* [50] and *Tochihara et al.* [50] in **Figure 4**. The predictions of the transient elderly TS model in step-change experiments (**Figure 4 (a-d)**) and gradual change experiment (**Figure 4 (e)**) were in good agreement with experimental TSV.

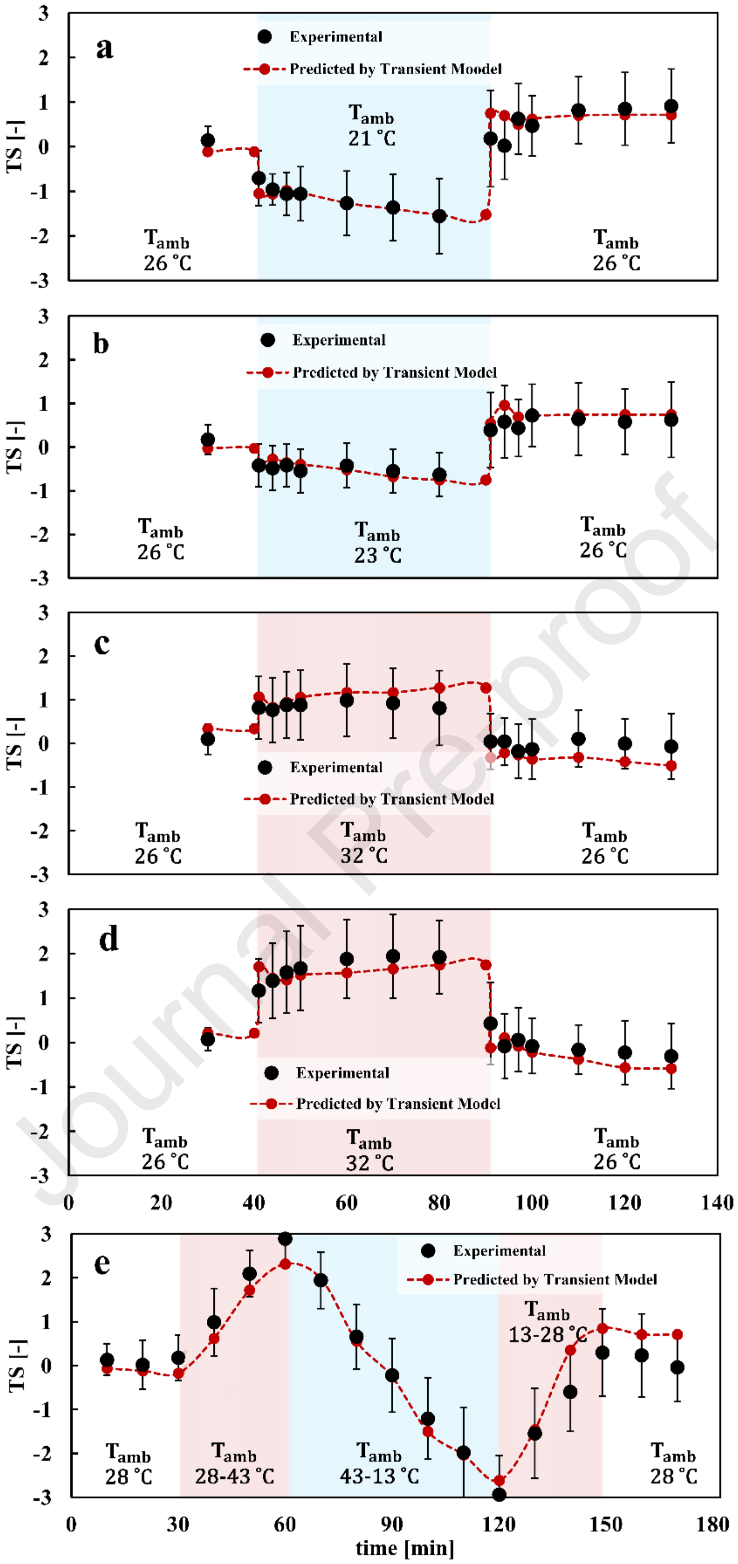

Figure 4 Experimental and predicted TS of sedentary subjects exposed to wide range of transient hot and cold conditions. markers represent means and error bars represent standard deviations (**a-d:** experiment of *Wang et al.* [50]; **e:** experiment of *Tochihara et al.* [50])

3.3.Elderly TS model validation under steady and transient conditions

The TS of old volunteers who took part in the *Soebarto et al.* experiment [55] was predicted using **Equation (4)** and compared to their subjective votes. **Table 4** summarizes the findings. The results are also included in **Figure 2**. The predicted TS was within the experimental data's standard deviation and close to its mean. Differences in TS for the same skin temperature between experiments or between participants within the same experiment (see error bars) are interpreted by individual differences in TS among the elderly.

Table 4 Validation of elderly TS model under steady state conditions from the experiment of *Soebarto et al.*

Case	**$T_{sk,av}$ [°C]**	**$T_{sk,av}$-$T_{sk,av,n}$ [°C]**	**TSV [-]**	**$TS_{predicted}$ [-]**	**Absolute Error [-]**
1	31.2	-2.13	-1.45 ± 0.9	-1.58	0.13
2	32.4	-0.98	-0.63 ± 1.1	-0.79	0.16
3	33.7	0.37	0.22 ± 0.7	0.46	0.24
4	34.2	0.82	1.23 ± 0.9	1.0	0.23

The developed transient TS model was used to predict the TS in the transient experimental settings of *Tochihara et al.* [57]. The results are shown in **Figure 5**. The model predicted well the TS of elderly subjects during transitions from neutral to cold (**Figure 5 (a)**), neutral to warm (**Figure 5 (b)**) as well as from cold and warm into neutral. The mean absolute error between predicted transient TS and mean experimental TSV is 0.292. The experiment included the effects of both $\Delta TS_{dT_{sk}}$ and ΔTS_{cr}.

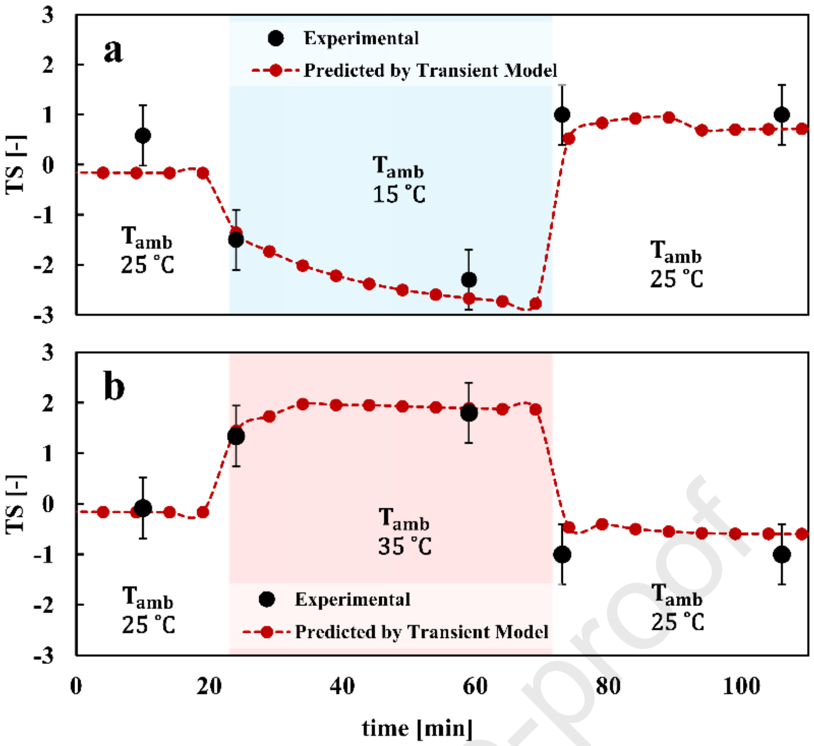

Figure 5 Experimental and predicted TS of sedentary subjects exposed to wide range of transient hot and cold conditions. markers represent means and error bars represent standard deviations (from the experiment of *Tochihara et al.* [57])

4. Elderly TS Model

In summary, the elderly TS model presented in **Table 5** may be used to predict the mean TS of elderly individuals under transient thermal environments:

Table 5 Elderly TS model for steady and transient conditions at low typical activity

Elderly TS model

$$\mathbf{TS = 3\tanh\left(TS_0 + \Delta TS_{dT_{sk}} + \Delta TS_{cr}\right)}$$

Term	Condition	Value
$\mathbf{TS_0}$	$\Delta T_{sk,av} \geq 0\ ^\circ C$	$0.425\ \Delta T_{sk,av}$
	$\Delta T_{sk,av} < 0\ ^\circ C$	$0.275\ \Delta T_{sk,av}$
$\mathbf{\Delta TS_{dT_{sk}}}$	$\frac{dT_{sk,av}}{dt} \geq 0.06\ ^\circ C/min$	$1.6\ \frac{dT_{sk,av}}{dt}$
	$\frac{dT_{sk,av}}{dt} \leq -0.06\ ^\circ C/min$	$0.85\ \frac{dT_{sk,av}}{dt}$
$\mathbf{\Delta TS_{crsk}}$	$\Delta T_{sk,av} > 0\ ^\circ C, \frac{dT_{sk,av}}{dt} < 0\ ^\circ C/min$	$-0.295 - 0.102\Delta T_{sk,av} + 3.22\Delta T_{cr} + 9.827\Delta T_{cr}^2 + 31.167\Delta T_{sk,av}\Delta T_{cr} - 5.276\ \Delta T_{sk,av}\Delta T_{cr}^2$
	$\Delta T_{sk,av} < 0\ ^\circ C, \frac{dT_{sk,av}}{dt} > 0\ ^\circ C/min$	$0.260 - 0.267\Delta T_{sk,av} + 0.054\Delta T_{cr} - 7.009\ \Delta T_{cr}^2 + 25.003\Delta T_{sk,av}\Delta T_{cr} + 0.005\ \Delta T_{sk,av}\Delta T_{cr}^2$

***** $\mathbf{\Delta T_{sk,av} = T_{sk,av} - 33.33\ ^\circ C;\ \Delta T_{cr} = T_{cr} - 36.76\ ^\circ C}$

5. Limitations and Future Outlook

The developed model does not account for metabolic change resulting from activity. Furthermore, the model is only valid under homogeneous climatic circumstances and cannot be employed in cases when only some parts are locally chilled or heated. Furthermore, the influence of adaptation on TS was not considered when developing the model. The predictions of the model cannot be guaranteed for long-lived elderly (age = 89+), as recent field study found significant disparities between their TS and that of younger (age = 60 to 74) and older elderly (age = 75 to 88) [67]. The model is only applicable in situations where subjects can’t follow adaptable strategies and they have no control over their local environments. Finally, the experiments that were used for the development and validation of the model span an ambient temperature range of 13 °C to 43 °C. The model is only applicable in the conditions under which it was developed and tested.

Table 6 Summary for ranges where the model was developed and validated; *applying the prediction of the model outside of the specified ranges requires further investigation and availability of experimental data and cannot be guaranteed.*

Parameter	Applicability Range
Age Group	65±3 to 72.4±5.3
Ambient Temperature	13 °C to 43 °C
Step Changes in Temperature	Up to 10 °C
Activity	Low (sedentary)
Thermal Environment	Uniform
Clothing Insulation	0.1 clo to 1.06 clo
Mean Radiant Temperature	Close to air temperature

As for the applications of the developed elderly TS model, it can be used to provide an elderly-customized control for air conditioning systems in elderly houses. Given that elderly people prefer warmer thermal conditions, such an application has the potential to reduce the energy consumption of air conditioning systems in hot climates while meeting the thermal comfort needs of elderly occupants. To facilitate employing the TS model in these applications, TS was expressed in terms of measurable skin temperatures taken from chest and forearm. While the forearm temperature can be measured by sensors mounted on a wristband, the chest temperature can be measured using sensors embedded within textile or using a chest strap. Moreover, when expressed in terms of measurable skin temperatures, the TS model enables the design of monitoring devices that monitor elderly TS in real time and alert them to potential health risks.

6. Conclusion

This study develops and validates a TS model for older individuals. The model was developed from steady-state and transient-state climatic chamber experiments published in literature. In order to predict transient and steady TS given the environmental conditions, the developed TS model was coupled with an elderly physiological model which was used to predict physiological parameters from ambient conditions. The elderly TS was expressed in terms of average skin temperature deviation from neutral value under steady conditions. The transient component of TS was expressed in terms of rate of change of skin temperature during abrupt changes in ambient conditions and in terms of core and skin temperatures when the body stores heat. The TS model was validated and showed good agreement with experimental data not used in its development. In summary the developed TS model can predict older people mean TS taking into consideration their changed thermoregulatory functions in the following scenarios:

- Steady neutral, cold, and hot ambient conditions using the skin average temperature as an input.
- Transitioning periods of transient ambient conditions where step-change or gradual-change occurs using the skin average temperature and its rate of change as inputs.

- Transient ambient conditions starting from a non-thermoneutral temperature where the body stores heat using the core and skin mean temperatures as inputs.

The developed model was equipped with a correlation that allows for the non-invasive prediction of elderly people's TS from few segmental temperature readings. The elderly TS model and the correlation may help in achieving thermally comfortable environments for elderly people with optimized cost. Future work will focus on the development of active control strategies that use the predicted elderly TS in real-time to regulate the conditions of the built environment according to the comfort needs of the elderly.

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Appendix A: Correlation for predicting TS from segmental temperatures

The established TS model enables the prediction of elderly transient TS using the core and average skin temperatures as inputs. Monitoring the two parameters during regular activities of elderly people is impractical. Therefore, it is intended to estimate the two quantities $T_{sk,av}$ and T_{cr} from few skin segmental temperatures that are practical to be measured.

Predicting elderly TS with non-invasive skin temperature readings

The elderly bioheat model is used to predict $T_{sk,av}$, T_{cr} and skin temperature for different segments $(T_{sk,i})$ under the conditions of the transient experiments described in Section 2.1.2. Analyzing the data reveals that the chest and forearm skin temperatures $(T_{sk,chest}\ ,\ T_{sk,forearm})$ together form a reliable predictor for both $T_{sk,av}$ and T_{cr}. The two skin temperatures can also be monitored while engaging in daily activities. The product of two truncated polynomials was assumed as a profile for both the estimated mean skin temperature $T_{sk,av,est}(T_{sk,chest}, T_{sk,forearm})$ and the estimated representative core temperature $T_{cr,est}(T_{sk,chest}, T_{sk,forearm})$ as shown in **Equation 10** and **Equation 11** in Section 2.2.2. Regression analysis for transient experiments was used to determine the coefficients (b_0 to b_3) in **Equation 10** and (c_0 to c_3) in **Equation 11**. The coefficients were all derived from transient experiments. The obtained coefficients are presented in **Table A.1**. As shown in **Figure A.1 (a)** and **Figure A.1 (b)**, the estimated mean skin temperature and core temperature and the predicted values via the bioheat model are highly correlated.

Table A.1 Coefficients obtained by regression for **Equation (10)** and **Equation (11)**

Term	**Coefficient for $T_{sk,av}$ equation**	**Value**	**Coefficient for T_{cr} equation**	**Value**
Intercept	b_0 [-]	-23.870	c_0 [-]	40.941
$T_{sk,forearm}$	b_1 [$°C^{-1}$]	1.015	c_1 [$°C^{-1}$]	-0.126
$T_{sk,chest}$	b_2 [$°C^{-1}$]	1.171	c_2 [$°C^{-1}$]	-0.157
$T_{sk,forearm}T_{sk,chest}$	b_3 [$°C^{-2}$]	-0.015	c_3 [$°C^{-1}$]	0.005

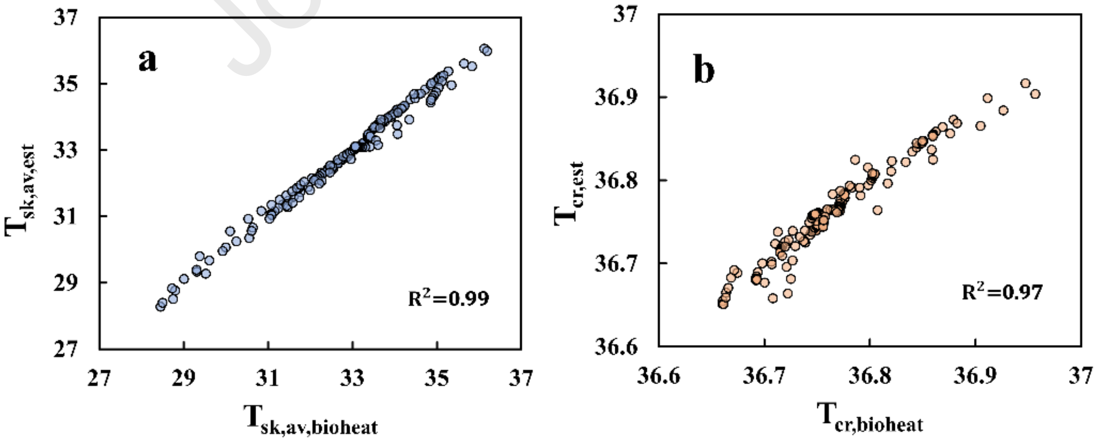

Figure A.1 **(a)** Correlation between $T_{sk,av,est}$ and $T_{sk,av,bioheat}$; and **(b)** between $T_{cr,est}$ and $T_{cr,bioheat}$

Validating the approach of predicting elderly TS from segmental temperatures

Here we present the validation approach for predicting elderly TS from segmental skin temperatures, namely $T_{sk,chest}$ and $T_{sk,forearm}$. Under steady conditions: the experimental work by *Xiong et al.* [30] offers measured segmental temperatures including $T_{sk,forearm}$ and $T_{sk,chest}$ as well as TSV of elderly subjects under various conditions. The elderly TS is therefore predicted from the measured segmental temperatures and then compared with experimental TSV. The validation results under steady conditions are presented in **Table A.2** and **Figure A.2 (a)** for steady state.

In order to validate the TS prediction using segmental temperatures during transient state, *Tochihara et al.* experiment [57] was employed. Segmental temperatures are not measured in this experiment. They are thus predicted utilizing the bioheat model. **Equation (10)** and **Equation (11)** were used to estimate the core and skin temperatures from $\mathbf{T_{sk,chest}}$ and $\mathbf{T_{sk,forearm}}$. The two segmental temperatures are then used to predict TS. **Figure A.2 (b)** presents the validation results for predicting elderly TS from segmental temperatures under transient conditions.

Table A.2 Validation of TS prediction from chest and forearm skin measured temperatures under steady state

Case	T_{amb} [°C]	$T_{sk,chest}$ [°C]	$T_{sk,forearm}$ [°C]	$T_{est,sk,av}$ [°C]	$TSV_{experimental}$ [-]	$TS_{predicted}$ [-]	Absolute Error [-]
1	21	32.55	30.58	30.83	-1.8 ± 0.5	-1.79	0.01
2	23	33.62	32.19	32.47	-0.6 ± 0.7	-0.70	0.10
3	28	34.60	33.78	33.97	0.8 ± 0.7	0.79	0.01
4	31	35.20	34.73	34.85	2.1 ± 0.8	1.71	0.39

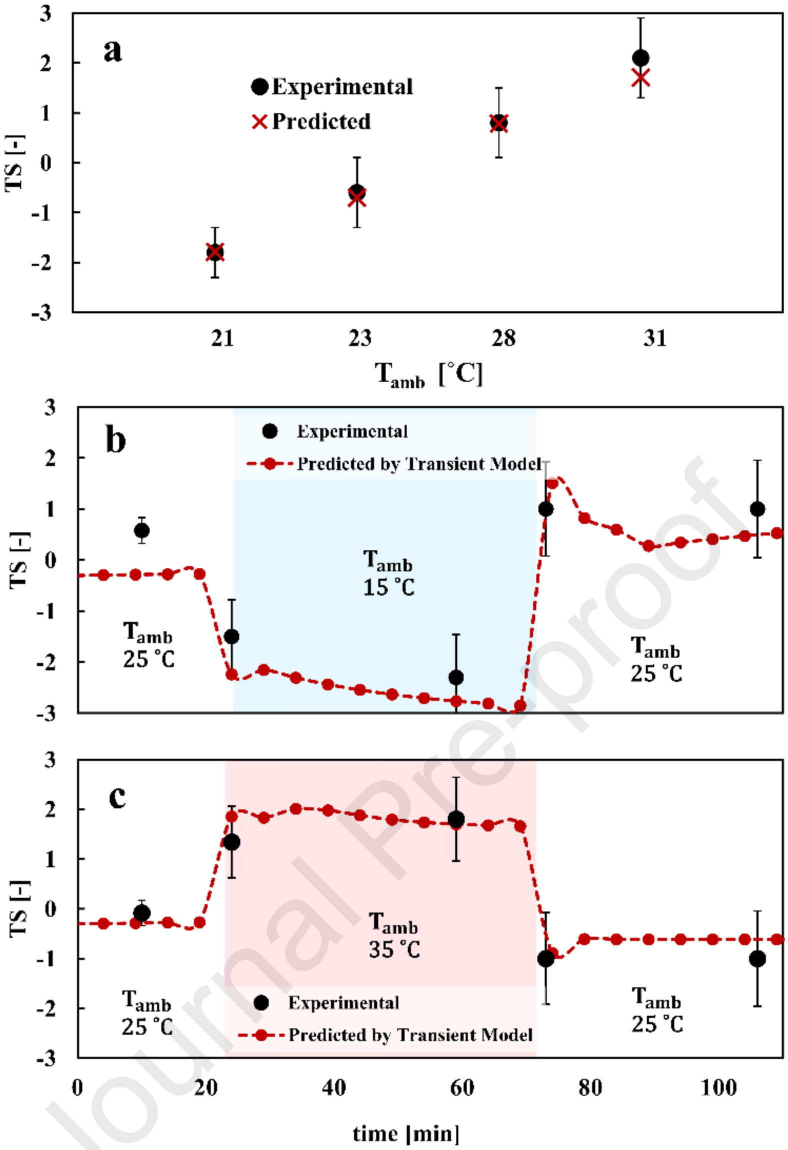

Figure A.2 **(a)** Validation of predicted elderly steady TS from segmental skin temperatures (chest and forearm) with experimental data (measured $T_{sk,i}$, TSV) from the experiment of Xiong et al. [30] **(b)** Validation of predicted transient TS from segmental skin temperatures with experimental data of *Tochihara et al.* [57]. (Red: $\mathrm{T_{amb}} = 25 - 35 - 25$ °C; Blue: $\mathrm{T_{amb}} = 25 - 15 - 25$ °C)

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Highlights

- Models for young adults are inadequate for predicting elderly thermal sensation
- An elderly thermal sensation model was derived from published experimental data
- TS model was validated with other published data for steady & transient conditions
- TS model applies to ambient range of 13 °C to 43 °C and to step changes up to 10 °C
- A correlation was developed to predict elderly TS from segmental temperatures

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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