Opportunities and challenges of using thermal comfort models for building design and operation for the elderly: a literature review

Zhou, S., Li, B., Du, C., Liu, H., Wu, Y., Hodder, S., Chen, M., Kosonen, R., Ming, R., Ouyang, L. and Yao, R. ORCID: https://orcid.org/0000-0003-4269-7224 (2023) Opportunities and challenges of using thermal comfort models for building design and operation for the elderly: a literature review. Renewable and Sustainable Energy Reviews, 183. 113504. ISSN 1879-0690 doi: https://doi.org/10.1016/j.rser.2023.113504 Available at https://centaur.reading.ac.uk/112564/

To link to this article DOI: http://dx.doi.org/10.1016/j.rser.2023.113504

Publisher: Elsevier

Opportunities and challenges of using thermal comfort models for building design and operation for the elderly: A literature review

Shan Zhou [a, b], Baizhan Li [a, b], Chenqiu Du [a, b], Hong Liu [a, b], Yuxin Wu [a, c], Simon Hodder [d], Minzhou Chen [e], Risto Kosonen [e], Ru Ming [a, b], Linyuan Ouyang [a,b], Runming Yao [a, b, f *]

[a] Joint International Research Laboratory of Green Buildings and Built Environments (Ministry of Education), Chongqing University, Chongqing, 400045, China

[b] National Centre for International Research of Low-carbon and Green Buildings (Ministry of Science and Technology), Chongqing University, Chongqing, 400045, China

[c] School of Civil Engineering and Architecture, Zhejiang Sci-Tech University, Hangzhou, 310018, Zhejiang, China

[d] School of Design & Creative Arts, Loughborough University, Loughborough, LE11 3TU, UK

[e] Department of Mechanical Engineering, Aalto University, Espoo, 02150, Finland

[f] School of the Built Environment, University of Reading, Reading, RG6 6DB, UK

Corresponding author E-mail addresses: r.yao@cqu.edu.cn (Runming Yao)

Abstract

In a progressively ageing society, providing thermally comfortable environments for the elderly has received attention from academics and practitioners. Thermal comfort models lay the foundation to promote the health and well-being of occupants of all ages and to achieve sustainable community goals. Most existing models are developed for healthy adults with a lack of understanding of thermal comfort specifically for the elderly which can result in mismatches between the elderly's thermal requirements and supply. This literature study aims to comprehensively analyse the existing research on this topic and identify deficiencies in knowledge. The literature analysis confirms that the commonly used Predicted Mean Vote and Predicted Percentage Dissatisfied (PMV-PPD) index and multi-node thermoregulation models contain limitations in their application for the elderly. The latter models were established based on existing thermoregulation models for young adults by integrating age-related physiological changes and thus have improved their predictive accuracy but this requires further research. The thermal sensation and adaptation measures of the elderly have unique characteristics. The effects of thermal adaptation are mainly reflected in the clothing regulating behaviour, physiological skin temperature changes, and the psychological effects of economic factors. This literature review highlights that there is an urgent need to develop elderly-based thermal comfort models considering ageing-related factors, including adaptation approaches. The prospected research direction attempts to fill the

existing gaps and contribute to the body of knowledge about the elderly's thermal comfort whilst laying the foundation for indoor environmental design and operation to support the elderly's health and well-being.

Highlights

- The PMV index faces challenges in application in indoor environments for the elderly.
- Multi-node thermoregulation models are inadequately studied and insufficiently used.
- The elderly have higher neutral temperatures and wider comfort ranges than the non-elderly.
- Insights are offered into thermoregulation models and adaptive regression models.
- Automatic building management systems offer future application opportunities.

Keywords

Thermal comfort; thermal sensation; elderly people; aged; adaptation; thermoregulation; indoor environment

Word count

9990 words excluding title, author names and affiliations, keywords, abbreviations, table/figure captions, acknowledgments, and references.

Nomenclature

Abbreviations

AC	Air-conditioned
AVA	Arterio-venous anastomoses
CH	Care homes
IoT	Internet of things
IP	The Iberian Peninsula
IRT	Infrared thermography
JOS	Jointed circulation system

NV	Naturally ventilated
PMV-PPD	Predicted mean vote and predicted percentage dissatisfied
RB	Residential buildings
RH	Radiative heated
TSV	Thermal sensation votes

Symbols

clo	Unit of clothing insulation, 1 clo = 0.155 m^2K/W
T_a	Air temperature, ˚C
T_{op}	Operative temperature, ˚C

1. Introduction

Worldwide, the ageing population has become an increasing challenge to economic growth and social care [1,2]. According to the prediction of the United Nations Department of Economic and Social Affairs, the percentage of the elderly (more than 60 years old) in the world will reach 18.1%, and 22.0% in 2035, and 2050 respectively [3]. Elderly people spend most of their time indoors daily [4]. Comfortable indoor environments can greatly influence their health [5], well-being [6–8], and community sustainability [2], which are key elements of Sustainable Development Goals [9]. The question remains open whether or not existing dwelling stocks provide protection against heat and cold for the elderly. Some scholars have responded to the question with negative answers because of the evidence of the reports of thermal dissatisfaction [10], indicating challenges in indoor comfort and the health of the elderly [11]. For example, uncomfortable warmth was discovered due to overheating in summer [12,13] and high heating temperatures in winter [14], while cold discomfort was found because of low indoor temperatures [13,15–18]. Moreover, indoor temperature fluctuations [19] and higher temperature steps between indoors and outdoors [16,19,20] were reported in winter and associated with the elderly’s thermal comfort.

Given the unfavourable thermal condition in elderly people’s dwellings, the cause of the problem was identified to be the mismatch between the elderly’s thermal requirements and the operation of heating and cooling systems [14]. A key barrier to solving the thermal discomfort problem of the elderly is a lack of understanding of their fundamental thermal requirements. To estimate the elderly’s thermal requirements, thermal comfort models for the elderly have been established in previous studies [21–27] aimed to develop links between thermal environments and human thermal responses. However, the research gap is an absence of a comprehensive summary of the current thermal models and the requirements of the elderly. Such knowledge can contribute to a further understanding of the application hurdle of the models and provide insights into future developments.

The overarching aim of this research is to summarise existing literature and provide research directions in elderly thermal comfort models. To achieve this goal, it is essential to 1) overview the *status quo* of the existing models for the elderly and analyse their thermal responses and characteristics, 2) gather evidence of the application status of the models for meeting their thermal requirements, and 3) analyse their limitations in practice and provide future directions.

2. Methods

For the purpose of this review, the elderly population is considered to be people 60 years and above [23,27,28]. To achieve the above-mentioned research aims and objectives, a systematic literature review [29] was used to identify and screen related articles. To further classify the model types of this study, a bibliometric analysis software Citespace [30] was used, which has been a widely used scientometric tool to analyse the frequency and co-occurrence of the keywords [31][32][33].

The processes of literature search, screening, and analysis are shown in Fig. 1. Firstly, the systematic review considered literature from the "Web of Science" Core Collection, Google Scholar, and Scopus databases. The literature search selected a combination of topics including "elder* OR aged people OR older people OR age difference" AND "thermal sensation OR thermal percept* OR thermal comfort* OR therm*regulat*" AND "model". The 362 eligible records were further restricted to the English language, and only peer-reviewed research articles and review articles were chosen to ensure research quality. Based on looking through the journal, title, and abstract, a list of topics not relating to the research aim was further excluded, including "outdoor* OR kindergarten OR school OR university OR child* OR infant*". Secondly, detailed scanning and screening relevant to thermal comfort models took place by reading the research titles and abstracts. Duplicates were excluded from the research list, thus 180 records were selected as eligible. Additionally, dissertations and standards were also examined to achieve the research goals. The references in the above-mentioned articles were also consulted to track the origin and sources of information.

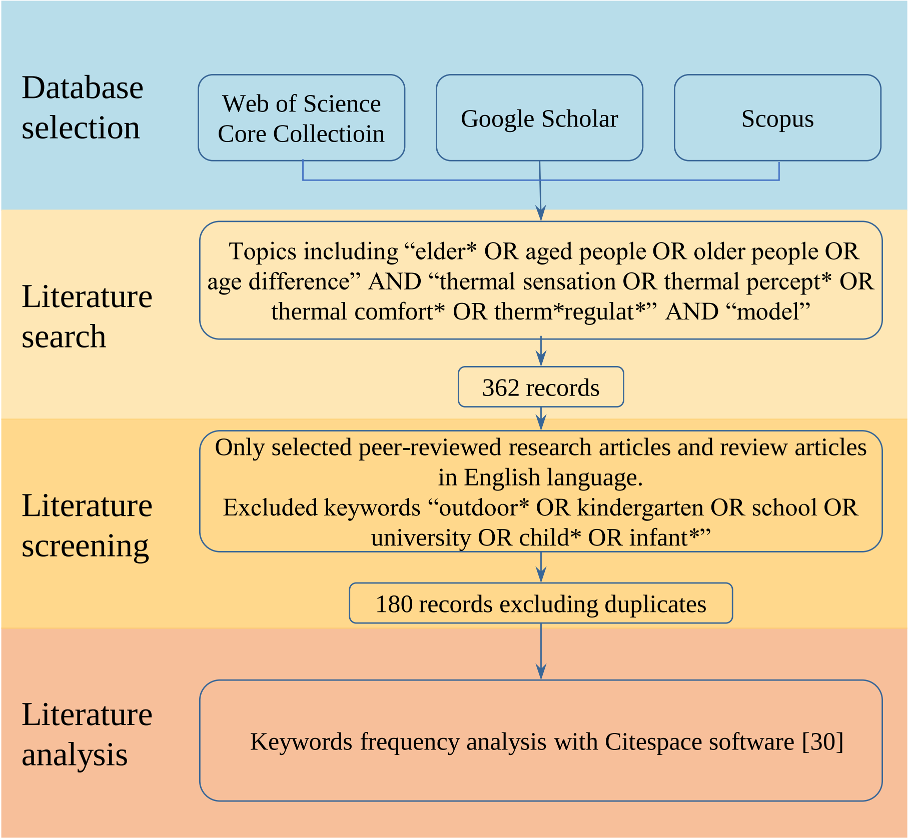
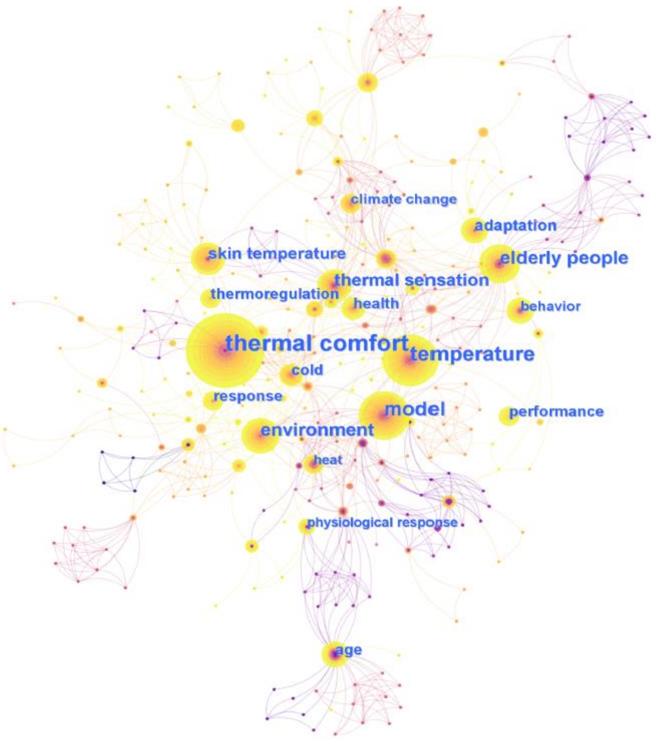


Fig. 1. The processes for literature search, screening, and analysis.

To further determine the commonly used models for the elderly, keyword frequency was recognized and analysed using Citespace 6.1.3 version [30]. The keyword information of the 180 records was input in the software, and "node types" of "keyword" was selected. The results identified 446 keyword nodes as plotted in Fig. 2. The size of nodes represents the frequency shown in the research records. Lines represent connections between keywords, indicating two keywords appear simultaneously in the same study. The most frequently used keywords were "thermal comfort", "temperature", "model", "elderly people", and "environment", which closely fell within the scope of this research. Moreover, the keywords "thermoregulation", "skin temperature" and "performance" indicate a high frequency of thermoregulation research. "Thermal sensation", "adaptation", "behaviour" and "physiological response" represent another widely used model: the adaptive regression model. Based on the bibliometric analysis, focusing on the research aim, the study's main concerns are with thermoregulation models and adaptive regression models. Accordingly, the structure and review contents are shown in Fig. 3.



Keyword	Frequency
Thermal comfort	75
Temperature	41
Model	34
Elderly people	27
Environment	24
Thermal sensation	23
Skin temperature	20
Adaptation	15
Age	14
Cold	14
Health	14
Performance	14
Response	14
Thermoregulation	14
Climate change	12
Behaviour	11
Heat	10
Physiological response	10

Fig. 2. Visual analytics of keyword co-occurrence and frequency from the 180 articles.

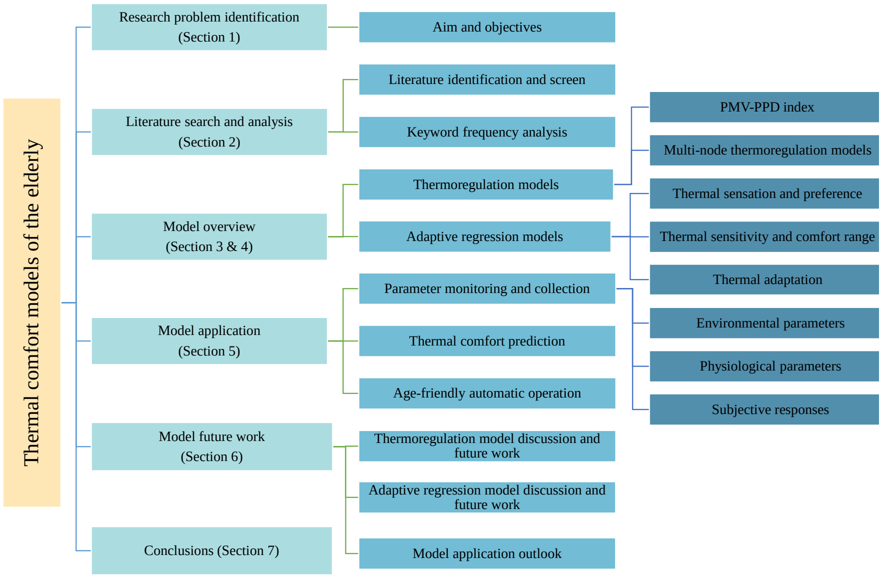


Fig. 3. The structure of the review contents.

3. Thermoregulation models of the elderly

Thermoregulation models are mathematical simulations of how the human body regulates its temperature in response to various environmental factors. Thermoregulation models are effective tools to model the heat transfer and thermal balance processes of the human body which can replicate the physiological reactions and intricate heat transport processes of the human body under diverse thermal ambient circumstances [34,35]. Since the establishment of the PMV-PPD index (one-node model) in 1970 [36], Gagge's two-node model in 1971 [37], and Stolwilk's multi-segment multi-node model in 1971 [38], the reviewed development history of thermoregulation models [34] has shown that the fundamental driver behind the development of thermoregulation models was the capacity to predict core temperatures and local/mean skin temperatures in various environmental situations. With this capacity, the predicted core and skin temperatures were first used in the aerospace industry for the thermal safety of astronauts [38]. It was then enlarged and developed in automobile and building environments. The prevailing thermoregulation models for the elderly mainly comprise PMV-PPD index [36] and multi-node thermoregulation models [35].

3.1 Performance of PMV-PPD index for the elderly

Fanger's PMV-PPD index has been a well-known approach that simplifies the human body as a one-node model [39]. The index determines a range of comfort temperatures that building occupants will find agreeable by linking human heat balancing with thermal sensation. It was developed from comparative experiments conducted by Fanger [36]. The experiments involved 128 healthy elderly individuals with a mean age of 68 years and 128 college-age young people with a mean age of 23 years. Both groups had an equal distribution of genders. The experiments consisted of eight different conditions, with four air temperature (T_a) levels (21.1, 23.3, 25.6, and 27.8°C), each paired with two relative humidity levels (30% and 70%). Each condition lasted for three hours, preceded by a 30-minute pre-test period. Thermal sensation votes (TSV) were collected six times at 30-minute intervals. By analysing the relationship between TSV and ambient temperature, it was found that the neutral temperature for both groups was 25.71°C [36].

The PMV-PPD index has been widely used in existing international and national standards and the standards' provisions of PMV ranges for the elderly are shown in Table 1. Following the results of earlier studies [36,40,41], ASHRAE 55-2020 [42] and ISO 7730-2005 [43] acknowledged no significant difference concerning neutral temperature and thermal comfort between the young and the elderly. By comparison, EN 16798-2019 [44] and CIBSE guide A [45] categorized the elderly with the narrowest comfort range ($-0.2 < \text{PMV} < 0.2$) considering the elderly's special needs. ISO 28803-2012 [46] suggested an acceptable temperature range as $0 < \text{PMV} < 0.5$ considering the elderly's lower activity level with a higher neutral temperature, as well as a lack of vasoconstriction and decreased thermal sensation.

Table 1. PMV-PPD index in thermal comfort standards for the elderly.

Standard	Category	PMV	PPD
ASHRAE 55-2020 [42]	Acceptable	[−0.5, 0.5]	< 10
	A	[−0.2, 0.2]	< 6
ISO 7730-2005 [43]	B	[−0.5, 0.5]	< 10
	C	[−0.7, 0.7]	< 15
EN 16798-2019 [44]	I	[−0.2, 0.2]	< 6
CIBSE guide A-2019 [45]	I	[−0.2, 0.2]	Not given
ISO 28803-2012 [46]	Acceptable	[0, 0.5]	Not given

The theoretical PMV-PPD index is capable of predicting the trends in thermal sensation. However, in most of the cases comparing actual TSV of the elderly and the PMV-PPD index [1,4,13,20,47–54], it was shown that the PMV-PPD index was not sufficiently accurate to be used for older adults. Specifically speaking, some studies found the slope of the linear regression of TSV was lower than PMV [48,50] and the prediction accuracy of the PMV index was found to be inconsistent for TSV of older people on both sides [52]. Studies in winter found that TSV is higher than PMV on the cold side in urban areas [1,13,50], while the rural elderly had an even stronger tolerance of lower temperatures than their urban counterparts, as PMV was much lower than the actual TSV [20]. In comparison, in summer, TSV were insensitive to T_a changes and lower than the PMV index [49]. As a result, compared to what PMV anticipated, the elderly have a larger temperature range for comfort [50]. The above finding indicates that the elderly have distinct ways to perceive and adapt to thermal environments, so the PMV index faces challenges in evaluating indoor environments for the elderly.

3.2 Multi-node thermoregulation models and age-related physiological changes

To address the insufficient accuracy of the PMV index, researchers have explored and developed multi-node thermoregulation models. Multi-node thermoregulation models for young adults have been comprehensively and thoroughly presented in the review literature [34,35] and include both passive and active systems [55]. The passive system, also called the controlled system [34,35], is the simplified physical body that is controlled by the active system. The passive system is typically divided into several layers, for instance, bone, muscle, fat, skin, etc. The passive system responds to inner body heat produced by metabolic processes, and heat is transferred throughout the physical body by thermal conduction and blood circulation. Then, heat transfers between the body and the ambient environments through convection, radiation, evaporation, and respiration. In addition, clothing plays an important role due to its complex hygrothermal properties [34,55]. The active system, also called the control system, reflects the neural system's function. The active system is driven by temperature signals to keep the internal core temperature and skin temperature of the body within a specific range and is associated with thermoregulation activities in multiple body parts via vasoconstriction, vasodilation, sweating, shivering, etc. [56]. By entering ambient environmental parameters (T_a, mean radiant temperature, relative humidity, and air velocity) and some human-related parameters (metabolic rate and clothing insulation) into the models, the physiological responses such as core temperature, local/mean skin temperature, and change rate of skin temperature [34] can be predicted.

The prevailing human thermoregulation models are the Stolwijk model [38], the Fiala model [55,57,58], the Tanabe model [59], the Huizenga model [60], etc. The thermal sensation prediction models established based on these thermoregulation models are more accurate and applicable over a wider range compared to the PMV-PPD index [61,62]. However, the prevailing human thermoregulation models are established from data on young people exposed to various environmental circumstances, and the parameters used to set passive and active systems typically represent the average individual [56]. Recent research has revealed that the multi-node thermoregulation models mentioned above are unable to adequately predict older people's skin temperature [63]. Wang *et al.* [64] also found that both Zhang's [65] and Fiala's [57] models had their deficiencies when directly applied to elderly adults because the databases for elderly responses to thermal conditions are limited. The Stolwijk and the Tanabe models were tested by Tang *et al.* [66] and greater variations were found in the predicted local skin temperatures for all situations. Also, the models were more accurate in predicting older adults' mean skin temperatures under neutral and high temperatures than under low temperatures [66].

The limited accuracy of the multi-node models in the elderly, as mentioned before, is a consequence of weakened physical thermoregulation among the elderly. With age, certain physiological changes are occurring in the human body, impairing functions in various organs and changing the way it adapts to different thermal conditions [67]. The following age-related physiological changes have been widely identified as the basis of multi-node thermoregulation studies for the elderly [28].

Firstly, the metabolic rate is closely related to human age. The metabolic rate of the elderly was 5%−30% lower than young adults with a sedentary metabolic rate of 40.6−55.1 W/m^2 [23,68–71]. The slower metabolism is mainly due to the loss of muscle tissue and neurological changes [72]. Consequently, the elderly respond slower to cold exposure owing to reduced metabolic heat production.

Secondly, elderly people have decreased core and skin temperatures [71]. The core temperature correlates with the metabolic rate, so a lower core temperature is associated with a decrease in the heart rate and cardiac output due to insufficient heat accumulation. Accordingly, the cardiac output of the elderly varied between a minimum of 3.4% to a maximum of 40% lower than young adults [23,70]. Also, body fat percentage and body weight [73] were found to be higher with age, which can increase the thermal insulation of the human body and decrease skin temperature [74], along with changes in muscle weight and organ mass, as well as higher fat thickness (especially in the abdomen) [23].

Moreover, sweating and shivering in older people start at higher and lower temperatures respectively [75,76] compared with young adults. The thresholds for the onset of vasodilation and sweating varied among the elderly but are delayed from those of young adults by 0.5˚C and 0.21˚C, respectively [23]. Older people have decreased sweat secretion rate [77] and a delayed sweating onset, while in cold environments, elderly people have less effective peripheral vasoconstriction and delayed shivering onset [70].

3.3 Multi-node thermoregulation models customized for the elderly

In order to improve the prediction accuracy of the above-mentioned multi-node thermoregulation models for the elderly, many scholars engaged in reflecting the age-related physiological changes mentioned above have further developed and customized the models for the elderly. As a result, inputs of the passive system, including body configuration, individual parameters, blood circulation system parameters, etc. are modified, as summarised in Table 2.

Table 2. Modified multi-node thermoregulation models for the elderly.

Model	Number of segments	Number of total nodes	Weight	Height	Age	Gender	Body surface area	Body fat	Metabolic rate	Cardiac output	Blood flow	Fat thickness	Segment length	Segment radius	Heart rate	Muscle thickness
Novieto [56,73]	15	63	V	V	V		V	V	V	V						
JOS-3 [78]	17	83	I	I	I	I	F	I	F	F	F					
Rida *et al.* [28]	25	128	V	V	> 60		V		V	F	V	V				
Itani *et al.* [23]	25	128	V	V	> 60		F	V	F	F	F				F	
Hirata *et al.* [79]	51	cubic voxels of 2 mm	V	V	Mean: Elderly (67.8yrs); Aged (73.9yrs)		V									
Ma *et al.* [70]	17	68	I	I	I	I	F	F	F	F			F	F		
Coccarelli *et al.* [80]			F		I		F	F	F		F	F				F

Note:

V: Provided specific values.

F: Provided function.

I: Individualized values, arbitrary.

Novieto and Zhang [56,73] developed the Older Persons Model based on the model of Fiala [81] to enable a more accurate prediction of older people's heat and cold stress. Body configurations, metabolic rate, and cardiac output were modified to fit a typical elderly person. The coefficients of the control function of the active system have been modified using a genetic algorithm. The T_a range of experiments used to calculate the coefficients was between 5˚C and 42˚C, giving this model a broad application range and good predictions for the elderly.

Takahashi *et al.* [78] established a Jointed Circulation System (JOS)-3 considering ageing effects based on the Stolwijk model [38] and JOS-2 [82]. JOS-3 nominally modified brown adipose tissue activity, shivering, cardiac and skin blood flow, and sweating. Specifically speaking, non-shivering brown adipose tissue activity for elderly aged 60+ reduced to zero due to ageing while shivering thermogenesis reduced to 85% compared to persons aged in their 20s. Total cardiac outputs for those in their 60s and 70s or older were 75% and 70% of those of young adults (20–40s)with the same body surface area, respectively. Age effects on vasodilation and sweating for age > 60 years were given for each segment, representing the decreased thermal responses under warm conditions. In the conditions of older adults, JOS-3 had a greater mean skin temperature prediction accuracy than JOS-2.

Rida *et al.* established a bioheat model for the elderly [28] based on the bioheat model of Karaki [83]. The model focused on blood flow circulatory changes to predict skin and core temperatures for different segments of the body, particularly the fingers. According to sensitivity analysis, the threshold temperatures for the onset of sweating and vasodilation have been identified as influential parameters and modified in the active system. Validation of the model used published experimental data spanning a temperature range of 10˚C to 35˚C. Itani *et al.* [23] further modified Rida's elderly bioheat model [28] to accurately predict the thermal responses of the elderly in heat-stressed environments up to 40˚C. Their study emphasizes that the presence of arterio-venous anastomoses (AVA) function is essential for heat-induced vasoconstriction, so that warm blood cannot easily reach the human core when exposed to high temperatures.

Hirata *et al.* [79] developed a model to estimate body temperature and sweating during passive exposure to heat under 40˚C in the elderly. The passive system of the model was based on an existing voxel model, and the control function of sweating was modified as follows: the decline in sweating in the limbs was accounted for by adding a multiplier; and the threshold for inducing the sweating response in the elderly was increased by the deviation of skin temperature from the neutral condition, which represents the decrease in thermal sensitivity of the skin with age. Although this model's passive system was segmented into 51 anatomical regions including the skin, brain, and heart, it did not account for the potential redistribution of blood flow from visceral organs to the skin when calculating the variation in the skin's blood perfusion rate due to vasodilatation.

Ma *et al.* [70] modified the passive parameters of the elderly based on Zhou's model [84,85] and the later models were established based on the Fiala model [55] to customize for Chinese young people. Several parameters of the passive system can be individualized for groups of people with various body characteristics. However, although the model performed well in prediction ability and the application is promising, the physiological changes in the active system are pending clearer quantification.

Coccarelli *et al.* [80] built the model based on their previous thermoregulatory model [86], considering the changes in vascular elasticity, cardiac contraction, and bone mineral density in the passive system caused by ageing, as well as the changes in blood flow and sweating threshold in the control system.

Generally speaking, all the multi-node thermoregulation models for the elderly were established by modifying only the passive system parameters or both active and passive system parameters. Age differences in thermoregulation processes were quantified and higher prediction performances have been achieved compared to the models for young people. The proposed model can be used in the building design and operation phases, offering the possibility to predict the thermal stress and cold stress levels and the associated thermal comfort of the elderly [87].

4. Adaptive regression models of the elderly

The above-mentioned thermoregulation models are usually based on rational heat balance theory and laboratory studies. In comparison, adaptive regression models, as another prediction approach, are established in various field studies to find the relationship between "right-here-right-now" questionnaire surveys and environmental parameters based on adaptive approaches and linear regression analysis. The questionnaire surveys usually collect thermal perception questions (TSV, thermal acceptability, thermal preference, etc.). The measured indoor environmental parameters mainly include T_a, relative humidity, globe temperature, operative temperature (T_{op}), air velocity, etc. Thus, thermal comfort regression models reveal the connection between the indoor thermal environment and thermal perception. The main purpose of these studies was to understand the current environmental situation of the elderly and to elicit preferred/neutral/comfortable temperatures and comfort ranges. In the related studies, comparative studies were quite common, e.g. comparing age differences in thermal perception between elderly and young adults [48,51,88–92], urban and rural area's elderly's perceptions [19,20,93], climate types [16,91], etc. Moreover, influencing factors of thermal comfort were also investigated including behavioural adaptation and living habits [4,49,52,94], clothing insulation variations [4,19,50,95,96], etc.

It has been reported that most of the elderly prefer to live independently at home, however, an increasing number of elderly people live in care homes [51,63,97]. Therefore, residential buildings and care homes have become the main premises where elderly people live and current field studies are mostly concerned with these premises. The detailed information and corresponding thermal comfort regression models are shown in Table 3.

Table 3. Regression models of the elderly in existing studies.

Reference	**Location**	**Building type**	**No. of samples and age range (yr)**	**Season**	**Mode of operation**	**Thermal preference**	**Regression model**	**Neutral temperature**	**Comfortable temperature range (˚C)**
[49]	Chongqing, China	CH	119, 60–100	Summer	NV	Prefer cooling by NV than AC	TSV = 0.13 T_a − 3.2	T_a = 24.6˚C	80% acceptability: $T_{out} < 32.5$˚C
		RB	333, 60–94				TSV = 0.10 T_a – 2.3	T_a = 23.0˚C	
[13]	Shanghai, China	CH	672, 70–95+	Summer	NV	Neutral thermal environments	TSV = 0.128 T_{op} − 3.249	T_{op} = 25.4˚C	−1 < TSV < 1: T_{op} 28.2–29.9˚C
				Winter			TSV = 0.079 T_{op} − 1.310	T_{op} = 16.6˚C	−1 < TSV < 1: T_{op} 12.5–13.6˚C
[24]	Shanghai, China	RB	1040, 70–95+	Winter	NV	Close to neutral thermal sensation	TSV = 0.076 T_{op} − 1.273	T_{op} = 16.8˚C	−0.2 < TSV < 0.2: T_{op} 14.1–19.4˚C
				Summer		Close to neutral thermal sensation	TSV = 0.124 T_{op} − 3.145	T_{op} = 25.4˚C	−0.2 < TSV < 0.2: T_{op} 23.8–27.0˚C
				Mid-season		Neutral-warm environment	TSV = 0.036 T_{op} − 0.940	T_{op} = 26.1˚C	−0.2 < TSV < 0.2: T_{op} range of 20.6–31.7˚C
[25]	Shanghai, China	CH	1040, 70+	Summer	NV	0.8˚C higher than people aged 20–60	TSV = 0.112 T_{op} − 2.813	T_{op} = 25.1˚C	−0.5 < TSV < 0.5: T_{op} 10.4–30.0˚C
				Winter		4.4˚C and 6.1˚C lower than two groups aged 20-60 and 21 on average	TSV = 0.078 T_{op} − 1.306	T_{op} = 16.7˚C	
				Mid-season		Not given	TSV = 0.041 T_{op} − 1.008	T_{op} = 24.6˚C	
[16]	Rural Qiqihar (northeast China)	RB	87, 65.5 (mean) ± 7.2 (standard deviation)	Winter	"Chinese Kang", radiator, firewall	Prefer higher indoor temperatures than middle-aged people (40–49)	TSV = 0.056 T_a – 0.79	T_a = 17.32˚C	90% acceptability: T_a 8.39–26.25˚C
	Rural Shanghai (southeast China)	RB	113, 68.1 (mean) ± 6.8 (standard deviation)		AC or no heating	Similar to Shanghai CH	TSV = 0.075 T_a − 1.27	T_a = 16.91˚C	90% acceptability: T_a 10.24–23.6˚C
[92]	Xi'an, China	CH	834, 60–96	Summer	NV	Most prefer no change or cooler than the present	TSV = 0.135 T_{op} – 3.250	T_{op} = 24.1˚C	80% acceptability: $T_{op} < 30.3$˚C 90% acceptability: $T_{op} < 28.3$˚C

				Winter		Most prefer no change or warmer than the present	TSV = 0.068 T_{op} – 1.312	T_{op} = 19.4˚C	80% acceptability: T_{op} > 14.9˚C 90% acceptability: T_{op} > 17.1˚C
				Mid-season		Most prefer no change to the present	TSV = 0.126 T_{op} – 2.856	T_{op} = 22.6˚C	80% acceptability: T_{op} < 27.9˚C 90% acceptability: T_{op} <24.3˚C
				yearly		Higher than people in Xi'an aged 15–50	TSV = 0.076 T_{op} – 1.548	T_{op} = 20.4˚C	80% acceptability: T_{op} 14.9–30.4˚C 90% acceptability: T_{op} 17.7–27.7˚C
[98]	Inner Mongolia province, China	Mutual aid CH	216, 60–93	Winter	Heating by a coal stove and "Chinese Kang"	21.09˚C, which is 0.57˚C higher than neutral	TSV = 0.169 T_{op} – 3.461	T_{op} = 20.52˚C	80% acceptability: *To* 15.48–25.56˚C
[99]	Hong Kong, China	CH	181, 65–85+	Summer	AC, NV, and fan cooling	Warmer environments	TSV = 0, for 24˚C < T_{op} < 27˚C	T_{op} = 24−27˚C	T_{op} 24–27˚C
			213, 65–85+	Winter	NV, AC heating	Warmer environments	TSV = 0.79 T_{op} − 17.844	T_{op} = 22.6˚C	T_{op} above 23˚C
[53]	Hong Kong, China	CH	384, 60–97	Summer	NV, AC	2.2˚C higher than local officers aged 25–50	A decay of one PMV-unit every 25.3 years for the over-60s	T_{op} = 25.8˚C	T_{op} 25.3–26.3˚C for relative humidity within 50%–70%
[88] [4]	Taiwan, China	RB	87 elderly (60–82) and 318 non-elderly (11–83)	summer	NV, AC, electric fan	Elderly preferred 25.0˚C T_{op}; Non-elderly preferred 25.3˚C T_{op}	Elderly: TSV = 0.39 T_{op} – 9.84 Non-elderly: TSV = 0.30 T_{op} – 7.68	Elderly: T_{op} = 25.2˚C Non-elderly: T_{op} = 25.6 ˚C	80% acceptability: 23.2–27.1˚C for elderly, 23.0–28.6˚C for non-elderly
				Winter	NV, AC heating	Not given	Elderly: TSV = 0.28 T_{op} – 6.50	Elderly: T_{op} = 23.2˚C	80% acceptability: 20.5–25.9˚C
[50]	Korea	CH	114, 65–90+	Summer	NV, AC	Warm or slightly hot weather	TSV = 0.32 PMV + 0.15	T_{op} = 25−27˚C	TSV～0: T_{op} 25–27˚C
			102, 65–90+	winter	FH		TSV = 0.84 PMV + 0.15		
			182, 65–90+	Mid-season	NV		TSV = 1.16 PMV + 0.44		
			398, 65–90+	yearly	NV, AC, FH	Warm or slightly hot weather	TSV = 0.71 PMV + 0.04	T_{op} = 25−27˚C	TSV～0: T_{op} 25–27˚C
[100]	Seoul, Korea	CH	294, 65+	Sep. and Oct.	NV, AC	Not given	TSV = 0.2121 T_{op} – 5.1098	T_{op} = 24.1˚C	−0.5 < TSV < 0.5: T_{op} 21.7−26.4˚C −1 < TSV < 1: T_{op} 19.4 – 28.8˚C

[89,101]	Australia	CH	322 elderly (65+) and 187 non-elderly (<65)	Summer	NV, AC	Elderly preferred 23.2˚C, which is 1.5˚C higher than non-elderly (<65)	Elderly: TSV = 0.16 T_{op} – 3.664 Non-elderly: TSV = 0.29 T_{op} – 6.38	Elderly: T_{op} = 22.9˚C Non-elderly: T_{op} = 22.0˚C	80% acceptability: T_{op} 17.9–27.4˚C for elderly T_{op} 18.7–25.3˚C for non-elderly
				Winter	AC, radiator, and gas heater	Not applicable due to no significant correlation	Not applicable to elderly Non-elderly: TSV = 0.23 T_{op} – 4.88	Elderly: Not obtained Non-elderly: T_{op} = 21.2˚C	90% acceptability: T_{op} 19.1–26.2 ˚C for elderly T_{op} 19.8–24.2˚C for non-elderly
[51]	East coast of Spain	CH	476 elderly (46–99) and 147 non-elderly (adult, age not given)	Summer	Centrally controlled NV	Prefer 1.4˚C higher than non-elderly	Elderly: TSV = 0.2838 T_{op} – 7.1687 Non-elderly: TSV = 0.5599 T_{op} – 13.395	Elderly: T_{op} = 25.3˚C Non-elderly: T_{op} = 23.9 °C	90% acceptability: 23.2–28.4˚C for elderly 80% acceptability: 23.2–25.6˚C for non-elderly
[14]	Spain	CH	737 elderly (65–99) and 157 non-elderly (20–65)	Winter	Heating by fan-coil	Lower than non-elderly	Elderly: TSV = 0.115 T_{op} – 2.484 Non-elderly: TSV = 0.335 T_{op} – 7.331	Elderly: T_{op} = 21.6˚C Non-elderly: T_{op} = 21.9˚C	90% satisfaction: T_{op} 21.6–22.9˚C for elderly
[90]	Spain	CH	1482 residents and 439 non-residents (age not given)	Heating period (mainly in winter)	AC heating	0.3˚C higher than non-elderly	Elderly: TSV = 0.10 T_{op} – 2.3 Non-elderly: TSV = 0.30 T_{op} – 6.84	Elderly: T_{op} = 22.7˚C Non-elderly: T_{op} = 22.9˚C	Adaptive model: 18.3–27.0˚C for elderly 18.4–25.0˚C for non-elderly
				Cooling period	AC cooling	0.7˚C higher than non-elderly			Adaptive model: 18.7–29.0˚C for elderly 18.3–27.0˚C for non-elderly
				NV period along all the seasons	NV	1.1˚C higher than non-elderly	Elderly: TSV = 0.12 T_{op} – 2.8 Non-elderly: TSV = 0.32 T_{op} – 6.95	Elderly: T_{op} = 22.7˚C Non-elderly: T_{op} = 21.8˚C	Adaptive model: 19.7–29.5˚C for elderly 18.6–28.0˚C for non-elderly
[48]	Madrid region, Central Spain	CH	1233 elderly (mostly 65+) and 179 non-elderly (age not given)	summer	AC	The elderly prefer 2.4˚C higher than non-elderly	Elderly: TSV = 0.15569 T_{op} – 4.0227 Non-elderly: TSV = 0.356 T_{op} − 8.2524	Elderly: T_{op} = 25.6˚C Non-elderly: T_{op} = 23.2˚C	$-1 < TSV < 1$: T_{op} 19.4–32.3˚C for elderly T_{op} 20.4–26˚C for non-elderly
[91]	Csa-c climatic zones of the Iberian Peninsula (IP)	CH	2138 elderly (65+) and 552 non-elderly (age not given)	NV period	NV	The elderly prefer 3.5˚C higher than non-elderly	Elderly: TSV = 0.1799 T_{op} − 4.3813 Non-elderly: TSV = 0.2789 T_{op} − 5.8175	Elderly: T_{op} = 24.4˚C Non-elderly: T_{op} = 20.9˚C	$-1 < TSV < 1$: T_{op} 18.9–29.7 ˚C for elderly T_{op} 17.3–24.4 for non-elderly

Csa-m climatic zones of IP	The elderly prefer 0.9˚C higher than non-elderly	Elderly: TSV = 0.1231 T_{op} − 2.789 Non-elderly: TSV = 0.3191 T_{op} − 6.9458	Elderly: T_{op} = 22.7˚C Non-elderly: T_{op} = 21.8˚C	$-1 < TSV < 1$: T_{op} 14.5–30.8˚C for elderly T_{op} 18.6–24.9˚C for non-elderly
Csb climatic zones of IP	The elderly prefer 4.0˚C higher than non-elderly	Elderly: TSV = 0.0997 T_{op} − 1.8058 Non-elderly: TSV = 0.1235 T_{op} – 1.7371	Elderly: T_{op} = 18.1˚C Non-elderly: T_{op} = 14.1˚C	$-1 < TSV < 1$: T_{op} 8.1−28.1˚C for elderly T_{op} 6.0−22.2˚C for non-elderly

Note: AC- Air-conditioned;

NV- Naturally ventilated;

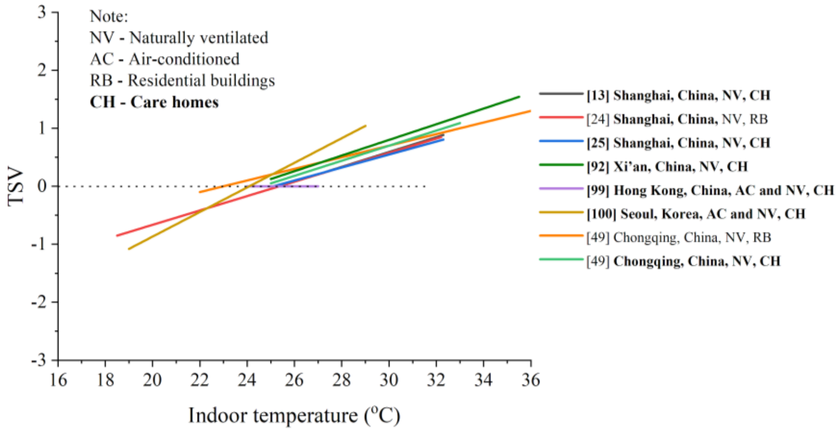
FH- floor heated;

RB- Residential buildings;

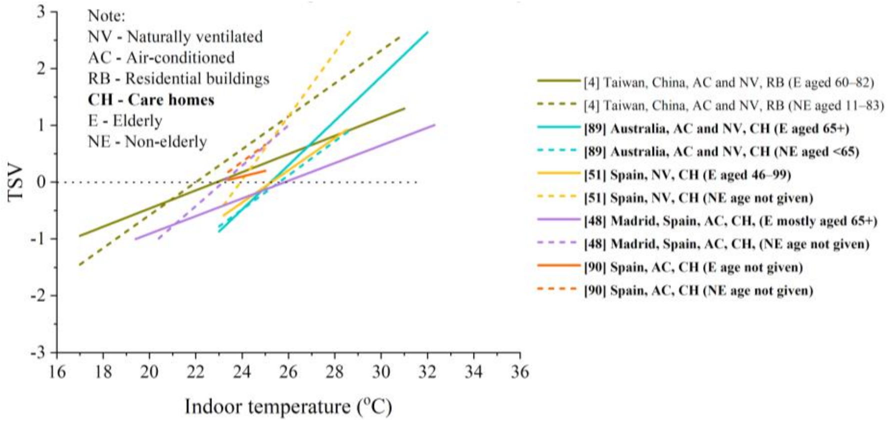
CH: Care homes

4.1 Neutral temperature and thermal preference

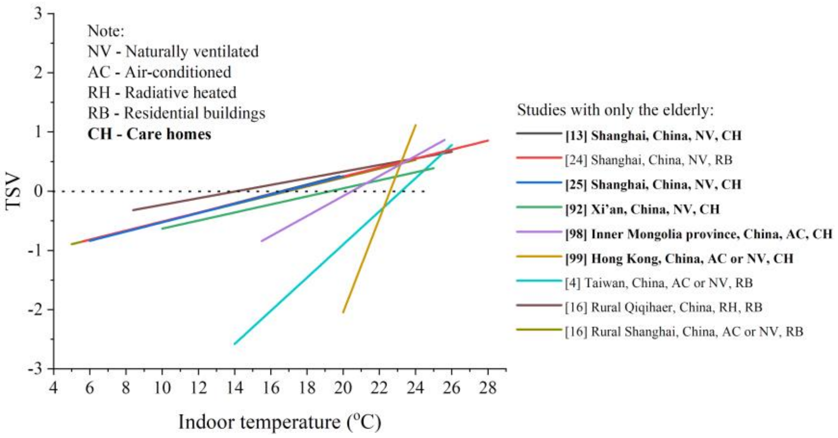
According to the information in Table 3, the thermal comfort regression models for the elderly were plotted in Fig. 4. Because seasonality was a factor in thermal perception, and the neutral temperatures (the intersections of regression models and the horizontal line with TSV equal to 0) of the elderly in summer are different from those in winter, the regression models were classified based on the season. The building types are grouped into residential buildings (RB) and care homes (CH), and the operation mode is also presented with air-conditioned (AC), radiative heated (RH), and naturally ventilated (NV).



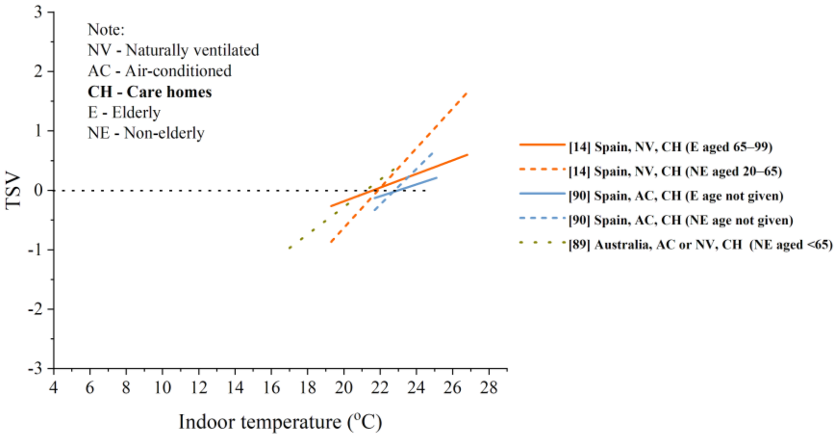
(a) Studies with only the elderly in summer/cooling season



(b) Comparative studies between ages in summer/cooling season



(c) Studies with only the elderly in winter/heating season



(d) Comparative studies between ages in winter/heating season

Fig. 4. Regression models of the elderly in the present studies.

Neutral temperature is an important measure of thermal comfort, and numerous studies have investigated the issue in field studies under sedentary states and freely adjustable garments. From Fig. 4(a) and (b) it can be seen that in most elderly cases (solid lines), the neutral temperatures in summer are in the range of 24.0–25.6˚C irrespective of building type and operating system (NV or AC cooling), which are higher than the non-elderly (dotted lines) under the same thermal environments. Only Tartarini *et al.* [89] and Wu *et al.* [49] found a lower neutral temperature of about 23˚C in the elderly. However, in winter the neutral temperatures in different studies are more diverse than in summer. For the naturally ventilated or decentralized buildings, the elderly have lower neutral temperatures with a range of 16.6–20.5˚C, while for the other heated buildings, the neutral temperatures of the elderly were higher at 21.6–23.2˚C. In most of the research, the elderly's neutral temperatures are higher than those of the non-elderly, whose reported age is typically less than 60.

In regard to indoor temperature on the horizontal axis, some research measured T_a [16,49] while others used T_{op}. T_{op} indicates the combined effects of heat radiation and heat convection. The calculation of T_{op} considers parameters including air temperature and mean radiant temperature [102], which can comprehensively evaluate thermal environments and reflect actual human thermal requirements. Thus, using the parameter T_a may neglect the radiative effect when subjects are near to windows or in radiatively heated rooms with "Chinese Kang" (heating the bed using the energy from coal or firewood) [103], radiator, and firewall [16].

In light of the details in Table 3, it can be seen that elderly people prefer neutral-warm indoor environments in all seasons. To be more specific, in summer, a preference for thermoneutral environments was found for the elderly in Shanghai, China [13,24], while the elderly in Hong Kong, China [99] and Korea [50] preferred warmer environments than neutral. In winter, a higher temperature than neutral was widely preferred by people with winter heating in Hong Kong, China [99], Inner Mongolia Province, China [98], Crete, Greece [76], and Korea [50], while a preference for thermoneutral environments was found for the elderly in Shanghai, China without winter heating [13,24]. In mid-season, neutral-warm environments in free-running buildings were preferred by the elderly in Shanghai, China [24] and Korea [50]. Thus, a neutral or warmer than neutral thermal sensation is preferred by the elderly all year through.

In addition to favouring neutral-warm surroundings, older people also preferred warmer environments to their younger counterparts (typically aged < 60). In summer, most of the elderly prefer higher temperatures than young adults with a range of 0.7–2.4˚C [25,48,51,53,89,90]. In mid-season when rooms were naturally ventilated, the elderly were also found to prefer higher temperatures with a range of 0.9–4.0˚C than college-aged young local people in Xi'an, China, [92] and Spain [90,91]. However, the age differences in thermal preferences in winter were related to the heating method. Compared with young adults, the elderly prefer higher indoor temperatures in Spain [90] and rural homes in northeast China [16], where heating systems were installed and frequently used. However, Shanghai elders adapted to low indoor temperatures without heating systems through higher clothing insulation and lower thermal expectations, as a result, they preferred lower temperatures than two local young groups by 4.4˚C and

6.1˚C, respectively [25]. The higher temperature preferences of the elderly were due to their lower levels of activity and lower metabolic rate [99] with less human body thermal dissipation.

The results obtained above are further compared with comfortable temperature ranges in existing standards. There are several standards regulating indoor T_a for the elderly. The Chinese code for indoor heating design temperatures for the aged [104] states that the rooms for long-term use should be kept to 20˚C. Especially, for the AC environment design [104], the thermal requirements of T_a, relative humidity, and air velocity are shown in Table 4. Based on Chinese culture and living habits, elderly people were assumed to prefer a higher temperature in both summer and winter compared to the occupants of general civil buildings (see Table 5) [105]. As a result, elderly people required an approximately 2˚C higher set point than the non-elderly, which is consistent with the results above.

Table 4. Indoor design parameters of air conditioning in long-term stay areas for the elderly (60+ years old) [104].

Type	T_a (˚C)	Relative humidity (%)	Air velocity (m/s)
Heating	22–24	N/A	≤ 0.2
Cooling	26–28	≤ 70	≤ 0.25

Table 5. Indoor design parameters of air conditioning in long-term stay areas in general civil buildings.

Type	Thermal comfort level	T_a (˚C)	Relative humidity (%)	Air velocity (m/s)
Heating	I	22–24	≥ 30	≤ 0.2
	II	18–22	N/A	≤ 0.2
Cooling	I	24–26	40–60	≤ 0.25
	II	26–28	≤ 70	≤ 0.3

The British guide (CIBSE Guide A) [45] states that for the living environments, the winter indoor temperature should be 22–23˚C with 1.0 clo (unit of clothing insulation, 1 clo = 0.155 m^2K/W) with heating. The summer indoor temperature should be 23–25˚C (0.6 clo) with cooling, which is lower than the Chinese stipulation of 26–28˚C. This may be because of the higher clothing insulation of British people, and that the climate of the UK is cooler than China in summer. EN 16798-1 [44] provides default design values for the elderly as category I with a sedentary activity of about 1.2 met. The minimum T_{op} for winter heating (1.0 clo) and maximum T_{op} for summer cooling (0.5 clo) are 21.0 and 25.5˚C, respectively. It can be seen that all the recommended temperatures fall in the range of thermal neutrality, or around 2˚C higher than the thermal neutral temperature. As a result, although the temperature ranges seem overly straightforward in the standards, the provisions remain instructive and valuable for the corresponding elderly people.

4.2 Thermal sensitivity and thermal comfort range

Thermal sensitivity has been used in field studies to describe the elderly's thermal sensation changes under thermal environmental variations [13,14,49], i.e. the slopes of the regression equations in Fig. 4. The higher the regression slope, the higher the thermal sensitivity, which means a higher change in TSV within the same temperature range. Fig. 4 shows that in summer, the slopes of the regression lines of the elderly were generally lower than those of young adults, which means the elderly were less thermally sensitive. The thermal sensitivities of the elderly were similar in care homes and varied in residential buildings in summer. That might be because the environmental conditions of the care homes and the health condition of the elderly in different care homes were similar. These two factors could vary significantly in residential buildings. All the regression coefficients for the elderly in mainland China were similar and much less thermally sensitive in winter than the studies in Hong Kong, China, which might be caused by the different climates and living styles. The elderly in Hong Kong [99] have high thermal sensitivity, the same as or even higher than that of young adults. The reason might be the warm climate in winter in Hong Kong with outdoor air temperatures higher than 16˚C, meanwhile, the indoor temperatures are mostly higher than 20˚C, and only when the indoor temperature is lower than 20 ˚C, do the staff turn on mechanical heating. The indoor temperatures were kept in the narrow range of 20–23˚C, making the adaptation ability of the local elderly lower.

In most cases, the elderly have lower thermal sensitivity than young adults [13,14,16]. As a result, it must be colder/warmer temperatures than other age groups before they report feeling cold/hot [14]. It has been reported that older adults have reduced warmth sensitivity in cold seasons [106] and reduced cold sensitivity in hot seasons [69,76]. Furthermore, elderly people were found to be even less sensitive to cold environments than to warm environments [4,13], because the decreases in the degree of sensitivity to cold stimuli were greater than for hot stimuli.

Comfortable temperature ranges were also investigated in various studies, as shown in Table 3. Elderly people have a greater tolerance for ambient temperature and have a broader acceptable temperature range than the young, particularly at the higher temperature end, depending on the local environment, the heating system, and the degree of their ability to adapt, which allows them to feel comfortable in a considerably wider range of temperatures [107]. The wider thermal comfort range in the elderly results in lower thermal non-acceptance and higher satisfaction rates in older subjects [108]. It is important to keep in mind that the elderly's lowest permissible temperature was not necessarily lower than that of younger people. For example, the lowest acceptable temperature for the Spanish elderly in naturally ventilated periods was similar to or higher than that of the young [90,91].

4.3 Influence of thermal adaptation

Thermal adaptation played an important role in the thermal perceptions of the elderly and the above-mentioned adaptive regression models. From the above, it was found that the ways of behavioural adaptation preferred by elderly people in different regions were diverse, and the difference was also evident between winter and summer [52]. Elderly people's living habits [99], clothing [96,109], and usage of heating and cooling devices [19] were found to vary between local climate [16,91], season [13,110], and building type [20,49]. From the thermal adaptation theory, adaptation is divided into behavioural, psychological, and physiological aspects. The following sections discuss these three aspects in detail.

4.3.1 Behavioural adaptation

For elders, the strategy of behavioural adaptation plays an important role in maintaining thermal comfort and the results of thermal comfort regression models. Many older individuals are skilled at utilizing diverse behaviours to obtain desired temperature preferences [96,111]. A study in Taiwan [4] found the most common thermal adaptation strategies adopted by elders in summer were window-opening, adjusting clothing, and the use of electric fans. By contrast, in winter approximately 64% of elders adapted to the indoor environments by adjusting clothing while 17% used mechanical heating [4]. In Australia, the strategies were adjusting clothing and the use of ceiling and portable fans in summer [89]. In Hong Kong, the most common strategies reported in summer were mechanical cooling, the use of electric fans, adjusting clothing, and opening windows; In winter, adjusting clothing was the most common strategy, followed by closing windows, mechanical heating, and taking a hot bath [99]. In

Shanghai, China and Australia [13,89], the elderly can actively react to environments by adjusting their clothing insulation and local air velocity. The above cases showed that the main behaviours for the elderly to adapt to thermal environments are changing clothing, regulating air speeds, and turning on heating and cooling systems.

Among these behaviours, the elderly mostly varied their clothing to adjust to thermal environments [13,25,71,89]. As for age difference, the elderly wore more clothing compared with the young adults due to their lower activity and metabolic rate. Especially, the lower the temperature, the higher the discrepancy in clothing insulation values between age groups. In Shanghai, older individuals' clothing insulation is 0.40 clo, 0.19 clo, and 0.09 clo higher than that of young people in mid-season, summer, and winter, respectively [25]. In Taiwan, when T_{op} dropped to 18˚C or lower, the clothing for the elderly was 0.25–0.35 clo higher than for young adults [4]. As for urban-rural differences, clothing worn by elderly people in rural houses (1.24 clo) was significantly heavier than in urban houses (0.93 clo) [19]. Regarding regional differences, the average clothing values for Korean and Shanghainese (Chinese) elderly were 0.39 and 0.44 clo in summer, and 0.78 and 1.38 clo in winter [50,95], respectively, while the Taiwanese elders and non-elders both wore 0.27 clo when the T_{op} exceeded 30˚C [4].

It was interesting to note that the usage of operating systems as another method of adaptation, diversely depends not only on the local weather and living habits but also on country policy. A large proportion of the studies were conducted in China. It was found winter indoor environments are varied because of the winter heating policy. The policy indicates that the urban area of northern China was mostly centrally heated with floor heating or radiators while dwellings in rest areas had decentralized heated or were not heated [112]. The decentralized heating systems are dispersed and diverse, including floor heating, radiative heating, AC heating, etc.

4.3.2 Physiological adaptation

Physiological adaptations include the body's immediate responses to real thermal environments, such as vasoconstriction and vasodilation to control blood flow in moderate situations, and perspiration and shivering in hot and cold conditions [113]. A variety of physiological parameters have been demonstrated to respond to temperature changes, including skin temperature, heart rate, blood pressure, tympanic temperature, heart rate variability, etc. [49,114,115]. Among the mentioned physiological parameters, local and mean skin temperatures have been widely studied and have been verified to be sensitive indicators to predict the elderly’s thermal sensation [49,100,114], as was mentioned in Section 3.2. For example, Tejedor *et al.* [109] proposed a human thermal response model using face skin temperature and clothing temperature with infrared thermography (IRT) to assist thermal comfort prediction and improve accuracy. Wu *et al.* also found that mean skin temperature was applicable for predicting thermal sensation for the elderly [49]. Another study in a transition season [100] found that local skin temperatures were useful in predicting thermal sensation in the elderly, especially the cheek and back of the hand. In addition, the difference in skin temperature between the thorax and foot was discovered to allow for roughly predicting the thermal comfort of the Chinese elderly [70]. The above content emphasizes the ability and great role of skin temperature in responding to environmental changes and indicating subjective thermal sensations.

4.3.3 Psychological adaptation

The financial issue has been an important factor influencing environmental decisions with thermal conditions being significantly influenced by income [116]. Tweed *et al.* [111] stated that older people’s attitudes toward money usage must be taken into account in addition to the physiological changes that come with ageing. Greek elderly consider it more important to heat their homes in the winter than to cool them in the summer because heating costs more than cooling does [76]. However, compared to active employees, older adults have lower incomes. Older individuals typically live in homes with lower indoor temperatures than those recommended by regulations [7]. As a result, the financial issue is noteworthy for elderly people’s thermal comfort and health. Moreover, better building design is essential to ensure that the residences are moderately comfortable without substantially relying on heating and cooling. For instance, reducing overheating with passive measures in summer and improving thermal insulation and air tightness in winter.

In addition, low expectations by the elderly result in few expressions of discomfort and dissatisfaction. Due to long-term living habits involving low heating use in winter, and long-term adaptation to the local climate, elderly people can adjust themselves by changing clothing and opening/closing windows and doors. As a result, the elderly’s desire to change the thermal environment is not as great as young people’s [20].

5. Present and potential applications of thermal comfort models for the elderly

According to the above findings considering age-related physiological changes and elderly people's different thermal requirements, occupant-centric control for the elderly to manage their well-being has been an important solution [117]. The above-mentioned thermal comfort models mainly showed the present thermal perception given heat balance and thermal adaptation respectively. How to further apply the models to building design and operation for the elderly has been a key jump from phenomenon summary to practical application. Thus, this section shows the present and potential applications of the investigated models following the three elements: monitoring, prediction, and control [117].

5.1 Parameter monitoring and collection

As the first step of indoor thermal environmental optimization, multiple related parameters can be monitored and collected, including environmental parameters, skin temperatures, clothing temperatures, metabolic rates, clothing insulation levels, subjective questionnaires, etc.

Environmental monitoring has been widely conducted in current field studies [1,16,18,52,118]. The monitored or measured parameters mainly include indoor T_a, relative humidity, air velocity, etc. Concerning the sampling rate, a 10 minutes interval for T_a monitoring was recommended [119]. However, according to the research method description, most of the present monitoring devices did not connect to the network, and the data is exported manually.

In addition to physical environmental parameters, as pointed out in Section 4.3.2, average and local skin temperatures have shown the potential to assist thermal comfort prediction. Also, the thermal exchange process through the skin-clothes-environment is complex. Clothing surface temperature, as the intermediate variable in the PMV calculation to enable estimating heat balance, is another important indicator. As IRT devices can collect temperature using a non-contact approach, it has a more flexible operating range than direct/contact temperature measurement. It is also possible to combine environmental parameters to predict thermal comfort in a variety of environments [120]. Multiple studies have used IRT on the elderly and have shown its convenience and ability to estimate thermal sensation [100,109,121,122]. The selected skin temperatures mainly include the nose, forehead, cheek, chin, hand, wrist, forearm, etc. The selection of body parts can be quite different due to the environmental settings, seasonal differences, and heating and cooling devices used in the studies.

With the development of Internet of Things (IoT) technology, it has become feasible to connect human physiological parameters and personal parameters with building management systems. Wearable and non-intrusive sensors have also been prevalent [123,124] due to their ability to estimate a variety of personal physiological parameters, such as metabolic rate [125], heart rate variability [126], local skin temperature [127], blood glucose [128], salivary cortisol [128], etc. Furthermore, age, gender, clothing insulation, and metabolic rate can also be predicted with the aid of vision-based technology and machine learning [129–131]. The estimation performance was reported to be accurate and reliable and effective in predicting thermal sensation and preference votes [132]. For example, Li *et al.* [127] used a smart wristband to assess human thermal sensation and established a thermal sensation assessment model of wrist skin temperature and timely heart rate through statistical and correlation analysis. However, the application of wearable sensors and the identification of personal parameters have limited validation in the present elderly research. Furthermore, given the lower cooperative awareness of the elderly, not all people are willing to wear them [109]. Privacy concerns may also make it harder to use and implement [109].

In addition to objective data collection, subjective thermal perceptions of the current thermal condition can also be collected. The frequently asked questions use a 7-point scale to collect thermal sensation data and a 3-point thermal preference scale in the present studies. The collecting method, in the above-mentioned surveys, is mostly through paper questionnaires and oral follow-up. With the increasing convenience of smartphone applications and human-machine interaction interfaces, questions can also be answered online. By using the thermal perception questionnaires, the thermal regression models for investigated groups or individuals can be further analysed, as described in the next section.

5.2 Thermal comfort prediction

For a group of people in a specific country, climate type, or adaptation extent, adaptive regression models or modified PMV-PPD index (for example, the methods used by the studies [1,50]) can be used to assess thermal conditions according to the research methods of the existing studies. Then, indoor thermal environments can be controlled to the proper range according to adaptive regression models or modified PMV-PPD index. The present results of adaptive regression models are convenient to use but have not involved monitored physiological parameters, and are unable to address individual preferences even under optimal conditions. To overcome these shortcomings, artificial intelligence methods such as machine learning have attracted increasing research attention for thermal comfort evaluation [122,133].

The application of emerging machine learning methodologies has brought solutions and alternatives for combining the above-mentioned new monitoring and sensing data [124,134]. For example, Liu *et al.* [124] developed a personal thermal comfort model that uses wearable devices to collect physiological signals during daily activities and predicts thermal preferences using different machine learning algorithms thus enabling the personal comfort model to achieve the highest prediction accuracy of 76%.

Existing machine learning models can not only be used with groups of people but can also be established for individuals to address individual differences [133,135,136]. The capability of prediction has been widely verified, with personal comfort models able to outperform PMV models with up to 74% greater accuracy, while machine learning models could outperform both PMV and adaptive models with up to 35.9% and 31% higher accuracy, respectively [137]. Thus, the integration of machine learning algorithms with thermal comfort data analysis is promising [138]. Additionally, when applied to various situations, by using their ability to self-correct machine learning models can automatically rectify or modify comfort correlations [139].

Among the established machine learning models, age has been recognized as an important feature [122], and studies [64,122,140–143] have established machine learning models for the elderly to predict their thermal sensations or thermal preferences. The data were collected from both field and laboratory studies, under the conditions of natural ventilation, fan cooling, temperature ramps, etc. The selected algorithms include random forest, deep learning, cluster analysis, neural network, and K-nearest neighbours. Unlike conventional thermal comfort models that require fixed input variables, input variables and learning algorithms in data-driven thermal comfort models are more flexible, and almost all machine learning algorithms can achieve better prediction performance compared to PMV models.

5.3 Age-friendly automatic control incorporating thermal comfort models

After predicting the thermal perceptions of the elderly, automatically controlling the devices and environments based on their requirements has been the final target. With the development of occupant-centric building operations and the IoT, building management systems have been the key solution for automatically addressing environmental discomfort for the elderly in the building operation phase. This automated technique can maintain thermal environments within a rational range, thus benefiting the elderly due to the inconvenience of them actively controlling their thermal environments. Especially, age-friendly automation is more urgent for those with dementia, physical disabilities, or requiring intensive care.

In an automated system, the input data can be a combination of the real-time environmental monitoring data, as mentioned in Section 5.1. The comfort range can be determined directly by the adaptive regression models or the modified PMV-PPD index obtained from collected questionnaires. Alternatively, it can also be determined by the machine learning models configured in the system. By comparing the difference between input data and target temperature, the building management system adjusts the corresponding actuators [109]. The actuators include personal comfort systems and both decentralized and centralized heating/cooling and ventilation devices. As a result, the thermal comfort purpose can be fulfilled from a local person to the building scale [117]. Moreover, lighting and solar shading systems can also be part of the control system to provide an integrated solution addressing thermal comfort as well as solar shading, visual comfort [99], visual safety [144], and mental health [145] for the elderly.

Another approach is based on a series of control strategies and schedules. For example, the research [146] has given a schedule based on field study, laboratory experiments, and building simulation to optimize the thermal environments of the elderly in summer in Thailand. The scheduled combined passive and active cooling strategies considering operation time and mode of different interventions, including natural ventilation, electric fans, and air conditioner. Thus, procedures to be adopted for the elderly integrating automatic control can be a promising solution.

However, such operating systems are rarely used in the present elderly studies. The challenge may be the high requirements of the automation system. Parametric monitoring and real-time data collection require the instrument to have sufficient storage and networking performance whilst the system control modules require sufficient local or cloud computing capacity. Currently, the effectiveness and convenience of age-friendly automatic operation systems remain to be further proven.

6. Future research and discussion

6.1 Insights of thermoregulation models

An intrinsic setting of the PMV-PPD index is that the mean skin temperature and sweat rate be maintained within a narrow range, but the elderly may not align with the values [77]. As a result, in-depth studies considering the elderly's changed body temperature set points and reduced thermal regulatory abilities are required for modification of the index. Additionally, age-related changes influenced thermal sensitivity [147], which can account for elderly individuals tending to rate their environments as less stressful than the PMV index estimates. Improving the PMV-PPD index to be closer to the actual TSV is needed to support revising the standards.

The reviewed multi-node thermoregulation models customized for the elderly in this research showed improvements in the prediction capacity of elderly people's physiological responses. The models are theoretical and explainable to reflect the actual thermophysiological regulation of the human body. However, the current studies reviewed which investigate multi-node thermoregulation models customized for the elderly are few in number, and the applications are limited.

Firstly, the model itself is not yet well developed, and basic physiological knowledge of older people is a requirement for the future. The human body's thermoregulation is much more complex than a simulated model, even though the reviewed models have divided the human body into a large number of nodes for thermal calculation. However, to date, the amount of data available on the thermophysiological responses of the elderly is far more limited than that for young people. The lack of detailed knowledge of how the body responds presents modelers seeking to produce a good effective model with a real challenge. For instance, the precise mechanism of blood circulation in the passive systems remains to be elucidated, and the optimizing method of the active system in existing studies needs further investigation.

Secondly, many of the existing elderly thermoregulation models are based on average data from specific healthy groups. The present data were mostly collected from healthy elderly groups due to ethical issues and disease factors. In reality, the huge variation in elderly people’s health and mental conditions, as well as medication, can impact their physiological functions (blood flow, metabolic rate, cardiac function), mobility, sensory function, etc. The issue of multiple health conditions that often afflict the elderly would be a confounding variable in any model. Considering health conditions enables expanding the scope of application to the less healthy elderly population. Also, personalization of the model is more likely to achieve accurate predictions and facilitate the application of personal comfort systems [148,149]. In the future perspective, the predictive accuracy of the thermoregulation models can be improved with individualized input values for the elderly, including age, health conditions, gender, physical parameters, etc.

Thirdly, unlike the PMV-PPD index, the outcomes of the multi-node thermoregulation models of the elderly are physiological parameters, and a small number of researchers have drawn on the research into relationships between the elderly’s physiological responses and thermal perceptions [114,115,147], which limits the application of the thermoregulation models. Predicting thermal sensation requires an additional model that employs the computed output of the thermoregulation model as the input [34]. The existing associations between physiological parameters and thermal perception widely established for the young may not be suitable for the elderly. A classic example is that elderly people are insensitive to temperature step changes without thermal sensation overshooting phenomenon [114,115]. As a result, thermoregulation studies would have been more useful if they had the thermal sensation modelling for elderly people. In addition, studies about the influence of perceptual degradation of the extremities on overall thermal sensation are also limited, especially under non-uniform environments (thermal radiation, thermal asymmetry, vertical temperature differences, etc.). The relationship between overall thermal sensation and local thermal sensation can shed light on the improvement of local comfort and individual comfort systems for the elderly.

6.2 Unraveling the findings from adaptive regression models

The findings from adaptive regression models have shown reduced thermal sensitivity and wider acceptability ranges of the elderly. To explain the age-related differences in thermal perception, the research further analyses the following reasons. One of the reasons is the reduced skin thermoreceptor function of the elderly [150]. The existence of cold and warm thermoreceptors can detect changes in skin temperature and further respond to temperatures by frequent action-potential discharge, and the density and functionality of skin thermoreceptors are lower in the elderly [150]. The other reason is the changed structures and functions of the nervous system [150], including the lower density of nerve fibres [109], decreased superficial skin blood flow [150], and decreased conduction velocity [151]. As a result, the detection of a threshold for thermal stimulation increases and is linked to lower thermal sensitivity. Moreover, the decrements in the limbs/distal parts are more pronounced than in proximal parts [56,150]. In addition, the lower thermal expectation makes the elderly less likely to complain about the environment and tend to avoid voting for the extreme option regarding the inability to change the environment [16,19,20]. The lower thermal sensitivity and lower thermal expectations result in the elderly's wider acceptable range. From the above information, it can be seen that low thermal sensitivity enables the elderly to be satisfied with both low and high temperatures, and the acceptable temperature can even be lower than 10˚C or higher than 30˚C. However, previous studies have reported that the minimum mortality temperature, as a health indicator [152], fell into the moderate temperature range of 18–30˚C [153]. Likewise, a Finnish decree limits indoor T_a to be below 30˚C for elderly houses from a health point of view [154]. With prolonged hot periods and more frequent heatwaves, the mortality risk for the elderly has greatly raised in recent years [155]. The elderly's detection of ambient temperature is impaired and they become more vulnerable than the healthy and young populations when exposed to thermal conditions outside the moderate temperature range [63,76,156]. Based on the above analyses, elderly people must be protected from excessively cold and hot indoor environments to reduce risks to their health [76].

It is worth noting that researchers are using different criteria to define the thermal comfort range, as shown in Table 3. Some studies defined comfort temperature range with 80% or 90% acceptability while some used TSV limit from −1 to 1 or −0.5 to 0.5. Additionally, studies using Griffiths' method mainly used 0.5 as the Griffith coefficient [13,90] while in Jiao *et al.* [24] used 0.25 as a constant for the winter, summer, and mid-season regression coefficient due to the lower thermal sensitivity of elderly people. In this regard, thermal comfort criteria and research methods can be various and may noticeably influence the results of the thermal comfort range. The question remains open as to whether future research can establish the correlation between thermal sensation, thermal comfort, thermal acceptability, etc. to establish connections among diverse research findings and enable better comparability. In doing so, a robust scientific basis can be formed for the development of unified criteria that define the thermal comfort range for the elderly.

6.3 Bridging the gap between adaptive regression models and thermoregulation models

Thermal comfort regression models directly link thermal environments with thermal sensation considering people's ability to adapt, which is useful for environmental design. Due to their reduced thermal sensitivity and wider acceptability range, the elderly have a lower percentage of dissatisfaction. However, the effects of thermal adaptation, even though grouped into three categories, are still hard to quantify, due to the complexity of people's interaction with thermal environments and the difficulty in enumerating the influencing factors. In this regard, theoretical and rational methods may fill the gap.

Several questions still remain to be answered in future field studies and adaptive regression models. The present adaptive regression models mainly focus on limited regions and climate types, and the building types mainly include care homes and residential buildings. However, the influence of building types is rarely discussed. Thus, a great focus on building a database could produce profound findings that account more effectively for the thermal adaptation of the elderly. More broadly, as shown in Section 4.1 and Table 5, most of the studies have provided neutral temperatures by linear regression. In addition to neutral temperatures, research is also needed to determine the preferred/optimal temperature for the elderly, which indicates the most comfortable temperature.

The pros and cons of thermoregulation models and adaptive regression models, as discussed previously, bring about new insights into addressing the application issues of the model. As skin temperatures of different body parts for heating and cooling have shown the prospect of higher prediction accuracy discussed in Section 4.3.3, skin temperature promises to become the bridge linking the theoretical physiological responses of thermoregulation models and the extent of adaptation presented by adaptive regression models. Indeed, a greater focus on bridging the gap between the two types of models could produce interesting findings that better account for the thermal perceptions of the elderly. However, traditional contact thermometry of local skin temperatures *in situ* is difficult. To address the issue, future studies can integrate non-contact infrared thermography [109] and wearable devices to measure sensitive body segments, e.g. forehead, hand, and cheek. Local and mean skin temperatures have been verified to be sensitive indicators to predict the elderly’s thermal sensation [49,100,114]. As the close association between skin temperature and thermal sensation, the correlation between local skin temperature, thermal environments, and thermal perception can be found.

6.4 Insights from the application of thermal comfort models of the elderly

In the building design stage, thermal comfort models can be used to define the optimal and comfortable thermal environments with the neutral/preferred temperature. By contrast, in the operation stage, it is more important to control thermal environments within the appropriate range and avoid overcooling and overheating. Owing to the development of IoT, the integration of thermal comfort models within an indoor operation system to assist the elderly to improve their living quality has become a possibility. The automation systems work in two ways by automatically switching windows and operating heating, cooling, and solar shading systems or by issuing warnings/messages to occupants/caregivers. In terms of indoor environmental parameter monitoring and collection, future devices interconnected with the IoT will become the basis of thermal comfort prediction and system automation. The networking can be Wi-Fi, wired, or cellular traffic. An effective strategy for studying indoor temperature conditions is real-time and long-term monitoring and analysis, which has the potential for use in the healthcare industry [118], but it is still challenging to link the data to building management systems.

From Section 5 it can be seen that human-centric building design and operation control provide solutions for achieving comfortable environments without heavy human intervention. With the increasing population of the elderly and higher requirements for quality intensive care, it is promising to achieve accurate thermal sensation prediction and automatic control with the development of technologies of IoT and building management systems. With clear group or individual thermal requirements, it would be possible to achieve a higher level of accuracy given more research on machine learning models.

6.5 Limitation of the present work

Due to the complexity of the elderly's thermal comfort issue and the broad scope of this literature review, there are still factors not explicitly discussed or quantified. For example, the geographical location and racial background were only given as information and the corresponding results in different studies were directly compared. As T_{op} is considered the most influential factor in this research, many of the above-described factors were only qualitatively described. Moreover, the age ranges in the reviewed studies fall into 60–100 years, which is a broad range. However, in the current work, it was not likely to assess the influence of age range, health status, personal preferences, and income level, thus only qualitative descriptions were performed. Assessing age differences among elderly people is still the subject of ongoing research and is limited by insufficient supportive data. Despite its limitations, the study certainly adds to new understanding of the current status of thermal comfort models for the elderly in terms of current research, application, and future directions. The thermal requirements and response characteristics of the elderly have been meticulously identified, paving the way for future research endeavors in this domain. Furthermore, the review of the application status of existing models has shed light on potential avenues for enhancing their practicality and relevance, particularly in meeting the specific thermal demands of the elderly population. By leveraging this knowledge, it becomes possible to elevate the application of these models to a higher level, ensuring that they effectively address and satisfy the unique thermal needs of older individuals.

7. Conclusions

Under the trend of the increasing ageing population, the thermal comfort and well-being of this population are significantly influenced by indoor thermal environments. The present thermal conditions in dwellings for the elderly indicate mismatches between their thermal requirements and building operation. The mismatch urges an in-depth understanding of the elderly's thermal requirements and further assists the environmental design and operation. Thus, this research comprehensively reviewed thermal comfort models for the elderly and their applications. Based on literature keyword analysis, the models were mainly categorized into thermoregulation models and adaptive regression models. The key findings are described as follows:

- There are mainly two types of thermoregulation models for the elderly, i.e. the

PMV-PPD index and multi-node thermoregulation models. The comfortable PMV ranges have been directly specified in numerous international and national thermal comfort standards for the elderly with the same or narrower PMV ranges than young individuals. However, some studies have suggested that the PMV-PPD index may not be as accurate when applied to elderly individuals. Multi-node thermoregulation models for the elderly are modified from already established models for young people by integrating age-related physiological changes. Some models changed only the passive system parameters of the body while others changed both active and passive system parameters. Higher prediction performances were achieved compared to the original models of young people, but are still in the early stages of research.

- The reviewed adaptive regression models show that existing field research on the elderly is mainly studied in residential buildings and care homes with natural ventilation and/or mechanical heating and cooling. The elderly's neutral temperatures tend to fall within the range of 24.0–25.6˚C in summer and 16.6–23.2˚C in winter. The elderly prefer neutral-warm environments all year round and prefer higher temperatures than the young in all seasons. Elderly people have lower thermal sensitivity and wider comfort ranges than young adults. The elderly have unique preferences for thermal comfort and adaption strategies. The most frequently adopted behaviours are clothing adaptation, regulating air speeds, and using heating and cooling systems. The elderly have higher clothing insulation in all seasons than the young group. Average skin temperature was found to be a sensitive physiological parameter to reflect thermal environments and the elderly's thermal sensations.
- The present application of thermal comfort models has three processes, i.e. parametric monitoring and collection, thermal comfort assessment, and automatic operation. The prevailing trend has shifted to using wearable devices and predicting personal thermal comfort using machine learning algorithms. The application of existing thermal comfort models for the elderly is limited, but age-friendly automatic operation using IoT and building management systems offers chances for the greatest possible comfort and convenience in the future.
- Future work to address the suitability of the PMV-PPD index for the elderly and to improve the accuracy of predicted thermal sensation will enable updating of the standard. Multi-node thermoregulation models for the elderly can be further

improved in terms of the configuration of the passive system, the control mechanism of the active system, model individualization, and association with thermal sensation. Bridging the gap between thermoregulation models and adaptive regression models could result in interesting findings that account more for the elderly’s thermal adaptation.

CRediT authorship contribution statement

Shan Zhou: Methodology, Writing - Original Draft . Baizhan Li: Supervision, Conceptualization. Chenqiu Du: Conceptualization, Review & Editing,. Hong Liu: Review & Editing, Project administration. Yuxin Wu: Analysis, Visualization, Writing. Simon Hodder: Review & Editing. Minzhou Chen: Analysis, Writing. Risto Kosonen: Review & Editing. Ru Ming: Data collection, Linyuan Ouyang: Data collection, Software. Runming Yao: Conceptualization, Supervision, Funding acquisition, Writing, Reviewing and Editing.

Acknowledgments

This work was supported by the National Key R&D Program of China [Grant No: 2022YFC3801504] and the Natural Science Foundation of Chongqing, China [Grant No: cstc2021ycjh-bgzxm0156]. The author acknowledges financial support from the Chinese Scholarship Council [No: 202206050102].

References

[1] Hughes C, Natarajan S, Liu C, Chung WJ, Herrera M. Winter thermal comfort and health in the elderly. Energy Policy 2019;134:110954. https://doi.org/10.1016/j.enpol.2019.110954.

[2] Jarzebski MP, Elmqvist T, Gasparatos A, Fukushi K, Eckersten S, Haase D, et al. Ageing and population shrinking: implications for sustainability in the urban century. Urban Sustain 2021;1:17. https://doi.org/10.1038/s42949-021-00023-z.

[3] United Nations. World Population Prospects 2022 2022. https://population.un.org/wpp/Download/Standard/Population/ (accessed December 14, 2022).

[4] Hwang RL, Chen CP. Field study on behaviors and adaptation of elderly people and their thermal comfort requirements in residential environments. Indoor Air 2010;20:235–45. https://doi.org/10.1111/j.1600-0668.2010.00649.x.

[5] Pronk NP, Kleinman D V., Richmond TS. Healthy People 2030: Moving toward equitable health and well-being in the United States. EClinicalMedicine 2021;33:100777. https://doi.org/10.1016/j.eclinm.2021.100777.

[6] Mendes A, Papoila AL, Carreiro-Martins P, Aguiar L, Bonassi S, Caires I, et al. The Influence of Thermal Comfort on the Quality of Life of Nursing Home Residents. J Toxicol Environ Heal - Part A Curr Issues 2017;80:729–39. https://doi.org/10.1080/15287394.2017.1286929.

[7] Salata F, Golasi I, Verrusio W, de Lieto Vollaro E, Cacciafesta M, de Lieto Vollaro A. On the necessities to analyse the thermohygrometric perception in aged people. A review

about indoor thermal comfort, health and energetic aspects and a perspective for future studies. Sustain Cities Soc 2018;41:469–80. https://doi.org/10.1016/j.scs.2018.06.003.

[8] Cascione V, Maskell D, Shea A, Walker P. A review of moisture buffering capacity: From laboratory testing to full-scale measurement. Constr Build Mater 2019;200:333–43. https://doi.org/10.1016/j.conbuildmat.2018.12.094.

[9] United Nations. The 17 Goals 2023. https://sdgs.un.org/goals (accessed February 6, 2023).

[10] Ormandy D, Ezratty V. Thermal discomfort and health: protecting the susceptible from excess cold and excess heat in housing. Adv Build Energy Res 2016;10:84–98.

[11] Farahani AV, Jokisalo J, Korhonen N, Jylhä K, Ruosteenoja K, Kosonen R. Overheating risk and energy demand of nordic old and new apartment buildings during average and extreme weather conditions under a changing climate. Appl Sci 2021;11. https://doi.org/10.3390/app11093972.

[12] Hughes C, Natarajan S. Summer thermal comfort and overheating in the elderly. Build Serv Eng Res Technol 2019;40:426–45. https://doi.org/10.1177/0143624419844518.

[13] Jiao Y, Yu H, Wang T, An Y, Yu Y. Thermal comfort and adaptation of the elderly in free-running environments in Shanghai, China. Build Environ 2017;118:259–72. https://doi.org/10.1016/j.buildenv.2017.03.038.

[14] Forcada N, Gangolells M, Casals M, Tejedor B, Macarulla M, Gaspar K. Field study on thermal comfort in nursing homes in heated environments. Energy Build 2021;244:111032. https://doi.org/10.1016/j.enbuild.2021.111032.

[15] Pinto M, Lanzinha J, Viegas J, Infante C, Freire T. Quality of the indoor environment in elderly care centers in two cities in central Portugal: Viseu and Covilhã. Int J Environ Res Public Health 2019;16. https://doi.org/10.3390/ijerph16203801.

[16] Chen Y, Zhang H, Yoshino H, Xie J, Yanagi U, Hasegawa K, et al. Winter indoor environment of elderly households: A case of rural regions in northeast and southeast China. Build Environ 2019;165. https://doi.org/10.1016/j.buildenv.2019.106388.

[17] Mendes A, Pereira C, Mendes D, Aguiar L, Neves P, Silva S, et al. Indoor Air Quality and Thermal Comfort—Results of a Pilot Study in Elderly Care Centers in Portugal. J Toxicol Environ Heal Part A 2013;76:333–44. https://doi.org/10.1080/15287394.2013.757213.

[18] Mendes A, Bonassi S, Aguiar L, Pereira C, Neves P, Silva S, et al. Indoor air quality and thermal comfort in elderly care centers. Urban Clim 2015;14:486–501. https://doi.org/10.1016/j.uclim.2014.07.005.

[19] Fan G, Xie J, Yoshino H, Yanagi U, Hasegawa K, Wang C, et al. Investigation of indoor thermal environment in the homes with elderly people during heating season in Beijing, China. Build Environ 2017;126:288–303. https://doi.org/10.1016/j.buildenv.2017.09.031.

[20] Zhang H, Chen Y, Rui J, Yoshino H, Zhang J, Chen X, et al. Effects of thermal environment on elderly in urban and rural houses during heating season in a severe cold region of China. Energy Build 2019;198:61–74. https://doi.org/10.1016/j.enbuild.2019.05.059.

[21] Wu Y, Zhang Z, Liu H, Li B, Chen B, Kosonen R, et al. Age differences in thermal comfort and physiological responses in thermal environments with temperature ramp. Build Environ 2023;228:109887. https://doi.org/10.1016/j.buildenv.2022.109887.

[22] Soebarto V, Zhang H, Schiavon S. A thermal comfort environmental chamber study of older and younger people. Build Environ 2019;155:1–14. https://doi.org/10.1016/j.buildenv.2019.03.032.

[23] Itani M, Ghaddar N, Ghali K, Laouadi A. Bioheat modeling of elderly and young for prediction of physiological and thermal responses in heat-stressful conditions. J Therm Biol 2020;88:102533. https://doi.org/10.1016/j.jtherbio.2020.102533.

[24] Jiao Y, Yu H, Yu Y, Wang Z, Wei Q. Adaptive thermal comfort models for homes for older people in Shanghai, China. Energy Build 2020;215:109918. https://doi.org/10.1016/j.enbuild.2020.109918.

[25] Wang Z, Yu H, Jiao Y, Wei Q, Chu X. A field study of thermal sensation and neutrality in free-running aged-care homes in Shanghai. Energy Build 2018;158:1523–32. https://doi.org/10.1016/j.enbuild.2017.11.050.

[26] Yochihara Y, Ohnaka T, Nagai Y, Tokuda T, Kawashima Y. Physiological responses and thermal sensations of the elderly in cold and hot environments. J Therm Biol 1993;18:355–61. https://doi.org/https://doi.org/10.1016/0306-4565(93)90059-3.

[27] Zheng G, Wei C, Li K. Determining the summer indoor design parameters for pensioners' buildings based on the thermal requirements of elderly people at different ages. Energy 2022;258:124854. https://doi.org/10.1016/j.energy.2022.124854.

[28] Rida M, Ghaddar N, Ghali K, Hoballah J. Elderly bioheat modeling: changes in physiology, thermoregulation, and blood flow circulation. Int J Biometeorol 2014;58:1825–43. https://doi.org/10.1007/s00484-013-0785-1.

[29] Snyder H. Literature review as a research methodology: An overview and guidelines. J Bus Res 2019;104:333–9. https://doi.org/10.1016/j.jbusres.2019.07.039.

[30] Chen C, Song M. Visualizing a field of research: A methodology of systematic scientometric reviews. PLoS One 2019;14. https://doi.org/10.1371/journal.pone.0223994.

[31] Li J, Liu N. The perception, optimization strategies and prospects of outdoor thermal comfort in China: A review. Build Environ 2020;170:106614. https://doi.org/https://doi.org/10.1016/j.buildenv.2019.106614.

[32] Yuan F, Yao R, Sadrizadeh S, Li B, Cao G, Zhang S, et al. Thermal comfort in hospital buildings – A literature review. J Build Eng 2021;45:103463. https://doi.org/https://doi.org/10.1016/j.jobe.2021.103463.

[33] Chen C. Science Mapping: A Systematic Review of the Literature. J Data Inf Sci 2017;2:1–40. https://doi.org/doi:10.1515/jdis-2017-0006.

[34] Katić K, Li R, Zeiler W. Thermophysiological models and their applications: A review. Build Environ 2016;106:286–300. https://doi.org/https://doi.org/10.1016/j.buildenv.2016.06.031.

[35] Fu M, Weng W, Chen W, Luo N. Review on modeling heat transfer and thermoregulatory responses in human body. J Therm Biol 2016;62:189–200. https://doi.org/https://doi.org/10.1016/j.jtherbio.2016.06.018.

[36] Fanger PO. Thermal comfort: Analysis and Applications in Environmental Engineering. Copenhagen: Danish Technical Press; 1970.

[37] Gagge AP, Stolwijk JAJ, Nishi Y. An Effective Temperature Scale Based on a Simple Model of Human Physiological Regulatiry Response. ASHRAE Trans 1971;13:21–36.

[38] Stolwijk JAJ. A mathematical model of physiological temperature regulation in man. Washington, D.C.: 1971.

[39] Djongyang N, Tchinda R, Njomo D. Thermal comfort: A review paper. Renew Sustain Energy Rev 2010;14:2626–40. https://doi.org/10.1016/j.rser.2010.07.040.

[40] Rohles FH. Preference for the thermal environment by the elderly. Hum Factors 1969;11:37–41.

[41] Sagawa S, Shiraki K, Yousef MK, Miki K. Sweating and cardiovascular responses of aged men to heat exposure. J Gerontol 1988;43:M1–8. https://doi.org/10.1093/geronj/43.1.M1.

[42] ASHARE. ANSI/ASHRAE Standard 55-2020 Thermal Environmental Conditions for Human Occupancy 2020.

[43] International Organization for Standardization. ISO 7730: Ergonomics of the thermal environment—Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria 2005.

[44] European Committee for Standardization. EN 16798-1 Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics 2019.

[45] The Chartered Institution of Building Services Engineers. CIBSE Guide A: Environmental design 2019.

[46] International Organization for Standardization. ISO 28803: Ergonomics of the physical environment—Application of international standards to people with special requirements 2012.

[47] Del Ferraro S, Iavicoli S, Russo S, Molinaro V. A field study on thermal comfort in an Italian hospital considering differences in gender and age. Appl Ergon 2015;50:177–84. https://doi.org/10.1016/j.apergo.2015.03.014.

[48] Baquero MT, Forcada N. Thermal comfort of older people during summer in the continental Mediterranean climate. J Build Eng 2022;54:104680. https://doi.org/https://doi.org/10.1016/j.jobe.2022.104680.

[49] Wu Y, Liu H, Li B, Kosonen R, Kong D, Zhou S, et al. Thermal adaptation of the elderly during summer in a hot humid area: Psychological, behavioral, and physiological responses. Energy Build 2019;203:109450. https://doi.org/10.1016/j.enbuild.2019.109450.

[50] Yang J, Nam I, Sohn J-RR. The influence of seasonal characteristics in elderly thermal comfort in Korea. Energy Build 2016;128:583–91. https://doi.org/10.1016/j.enbuild.2016.07.037.

[51] Forcada N, Gangolells M, Casals M, Tejedor B, Macarulla M, Gaspar K. Summer thermal comfort in nursing homes in the Mediterranean climate. Energy Build 2020;229:110442. https://doi.org/https://doi.org/10.1016/j.enbuild.2020.110442.

[52] Wang Z, Cao B, Lin B, Zhu Y. Investigation of thermal comfort and behavioral adjustments of older people in residential environments in Beijing. Energy Build 2020;217:110001. https://doi.org/10.1016/j.enbuild.2020.110001.

[53] Wong LT, Fong KNK, Mui KW, Wong WWY, Lee LW. A field survey of the expected desirable thermal environment for older people. Indoor Built Environ 2009;18:336–45. https://doi.org/10.1177/1420326X09337044.

[54] Schellen L, Van Marken Lichtenbelt WD, Loomans MGLCLC, Toftum J, de Wit MH, Lichtenbelt WD van M, et al. Differences between young adults and elderly in thermal comfort, productivity, and thermal physiology in response to a moderate temperature drift and a steady-state condition. Indoor Air 2010;20:273–83. https://doi.org/10.1111/j.1600-0668.2010.00657.x.

[55] Fiala D, Havenith G, Bröde P, Kampmann B, Jendritzky G. UTCI-Fiala multi-node model of human heat transfer and temperature regulation. Int J Biometeorol 2012;56:429–41. https://doi.org/10.1007/s00484-011-0424-7.

[56] Novieto DT. Adapting a human thermoregulation model for predicting the thermal response of older persons. De Montfort University, 2013.

[57] Fiala D. Dynamic simulation of human heat transfer and thermal comfort. De Montfort University, 1998.

[58] Fiala D, Lomas KJ, Stohrer M. A computer model of human thermoregulation for a wide range of environmental conditions: the passive system. J Appl Physiol 1999;87:1957–72. https://doi.org/10.1152/jappl.1999.87.5.1957.

[59] Tanabe SI, Kobayashi K, Nakano J, Ozeki Y, Konishi M. Evaluation of thermal comfort using combined multi-node thermoregulation (65MN) and radiation models and computational fluid dynamics (CFD). Energy Build 2002;34:637–46. https://doi.org/https://doi.org/10.1016/S0378-7788(02)00014-2.

[60] Huizenga C, Hui Z, Arens E. A model of human physiology and comfort for assessing complex thermal environments. Build Environ 2001;36:691–9. https://doi.org/https://doi.org/10.1016/S0360-1323(00)00061-5.

[61] Zhang H, Huizenga C, Arens E, Wang D. Thermal sensation and comfort in transient non-uniform thermal environments. Eur J Appl Physiol 2004;92:728–33. https://doi.org/10.1007/s00421-004-1137-y.

[62] Takada S, Matsumoto S, Matsushita T. Prediction of whole-body thermal sensation in the non-steady state based on skin temperature. Build Environ 2013;68:123–33. https://doi.org/https://doi.org/10.1016/j.buildenv.2013.06.004.

[63] van Hoof J, Schellen L, Soebarto V, Wong JKW, Kazak JK. Ten questions concerning thermal comfort and ageing. Build Environ 2017;120:123–33. https://doi.org/10.1016/j.buildenv.2017.05.008.

[64] Wang Z, Yu H, Luo M, Wang Z, Zhang H, Jiao Y. Predicting older people's thermal sensation in building environment through a machine learning approach: Modelling, interpretation, and application. Build Environ 2019;161:106231. https://doi.org/10.1016/j.buildenv.2019.106231.

[65] Zhang H. Human thermal sensation and comfort in transient and non-uniform thermal environments. UC Berkeley: Center for the Built Environment, 2003.

[66] Tang Y, Yu H, Wang Z, Luo M, Li C. Validation of the Stolwijk and Tanabe human thermoregulation models for predicting local skin temperatures of older people under thermal transient conditions. Energies 2020;13:6524. https://doi.org/10.3390/en13246524.

[67] Sato M, Kanikowska D, Sugenoya J, Inukai Y, Shimizu Y, Nishimura N, et al. Effects of aging on thermoregulatory responses and hormonal changes in humans during the four seasons in Japan. Int J Biometeorol 2011;55:229–34. https://doi.org/http://dx.doi.org/10.1007/s00484-010-0328-y.

[68] Tsuzuki K, Iwata T. Thermal comfort and thermoregulation for elderly people taking light exercise. Proc Indoor Air 2002;2:647–52.

[69] Tsuzuki K, Ohfuku T. Thermal sensation and thermoregulation in elderly compared to young people in Japanese winter season. Proc Indoor Air 2002:659–64.

[70] Ma T, Xiong J, Lian Z. A human thermoregulation model for the Chinese elderly. J Therm Biol 2017;70:2–14. https://doi.org/10.1016/j.jtherbio.2017.08.002.

[71] Wang Z, de Dear R, Luo M, Lin B, He Y, Ghahramani A, et al. Individual difference in thermal comfort: A literature review. Build Environ 2018;138:181–93. https://doi.org/10.1016/j.buildenv.2018.04.040.

[72] Choi J, Aziz A, Loftness V. Investigation on the impacts of different genders and ages on satisfaction with thermal environments in office buildings. Build Environ 2010;45:1529–35. https://doi.org/10.1016/j.buildenv.2010.01.004.

[73] Novieto DT, Zhang Y. Thermal comfort implications of the aging effect on metabolism, cardiac output and body weight. Proc. Conf. Adapt. to Chang. New Think. Comf. Wind. 2010, 2010.

[74] Budd GM, Brotherhood JR, Hendrie AL, Jeffery SE. Effects of fitness, fatness, and age on mens responses to whole-body cooling in air. J Appl Physiol 1991;71:2387–93. https://doi.org/10.1152/jappl.1991.71.6.2387.

[75] Anderson GS, Meneilly GS, Mekjavic IB. Passive temperature lability in the elderly. Eur J Appl Physiol Occup Physiol 1996;73:278–86. https://doi.org/10.1007/BF02425488.

[76] Giamalaki M, Kolokotsa D. Understanding the thermal experience of elderly people in their residences: Study on thermal comfort and adaptive behaviors of senior citizens in Crete, Greece. Energy Build 2019;185:76–87. https://doi.org/10.1016/j.enbuild.2018.12.025.

[77] Coull NA, West AM, Hodder SG, Wheeler P, Havenith G. Body mapping of regional sweat distribution in young and older males. Eur J Appl Physiol 2021;121:109–25. https://doi.org/10.1007/s00421-020-04503-5.

[78] Takahashi Y, Nomoto A, Yoda S, Hisayama R, Ogata M, Ozeki Y, et al. Thermoregulation model JOS-3 with new open source code. Energy Build 2021;231:110575. https://doi.org/https://doi.org/10.1016/j.enbuild.2020.110575.

[79] Hirata A, Nomura T, Laakso I. Computational estimation of body temperature and sweating in the aged during passive heat exposure. Int J Therm Sci 2015;89:154–63. https://doi.org/https://doi.org/10.1016/j.ijthermalsci.2014.11.001.

[80] Coccarelli A, Hasan HM, Carson J, Parthimos D, Nithiarasu P. Influence of ageing on human body blood flow and heat transfer: A detailed computational modelling study. Int j Numer Method Biomed Eng 2018;34:1–21. https://doi.org/10.1002/cnm.3120.

[81] Fiala D, Lomas KJ, Stohrer M. Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions. Int J Biometeorol 2001;45:143–59. https://doi.org/10.1007/s004840100099.

[82] Kobayashi Y, Tanabe S. Development of JOS-2 human thermoregulation model with detailed vascular system. Build Environ 2013;66:1–10. https://doi.org/https://doi.org/10.1016/j.buildenv.2013.04.013.

[83] Karaki W, Ghaddar N, Ghali K, Kuklane K, Holmér I, Vanggaard L. Human thermal response with improved AVA modeling of the digits. Int J Therm Sci 2013;67:41–52. https://doi.org/https://doi.org/10.1016/j.ijthermalsci.2012.12.010.

[84] Zhou X, Lian Z, Lan L. An individualized human thermoregulation model for Chinese adults. Build Environ 2013;70:257–65. https://doi.org/10.1016/j.buildenv.2013.08.031.

[85] Zhou X, Zhang H, Lian Z, Zhang Y. A model for predicting thermal sensation of Chinese people. Build Environ 2014;82:237–46. https://doi.org/10.1016/j.buildenv.2014.08.006.

[86] Coccarelli A, Boileau E, Parthimos D, Nithiarasu P. An advanced computational bioheat transfer model for a human body with an embedded systemic circulation. Biomech Model Mechanobiol 2016;15:1173–90. https://doi.org/10.1007/s10237-015-0751-4.

[87] Ji L, Laouadi A, Wang L, Lacasse MA. Development of a bioheat model for older people under hot and cold exposures. Build Simul 2022;15:1815–29. https://doi.org/10.1007/s12273-022-0890-3.

[88] Cheng M, Hwang R. Thermal comfort requirements in air-conditioned residences in hot-humid climate. Tongji Daxue Xuebao/Journal Tongji Univ 2008;36:817–22.

[89] Tartarini F, Cooper P, Fleming R. Thermal perceptions, preferences and adaptive behaviours of occupants of nursing homes. Build Environ 2018;132:57–69. https://doi.org/10.1016/j.buildenv.2018.01.018.

[90] Forcada N, Gangolells M, Casals M, Tejedor B, Macarulla M, Gaspar K. Field study on adaptive thermal comfort models for nursing homes in the Mediterranean climate. Energy Build 2021;252:111475. https://doi.org/https://doi.org/10.1016/j.enbuild.2021.111475.

[91] Baquero Larriva MT, Mendes AS, Forcada N. The effect of climatic conditions on occupants' thermal comfort in naturally ventilated nursing homes. Build Environ 2022;214:108930. https://doi.org/https://doi.org/10.1016/j.buildenv.2022.108930.

[92] Zheng W, Shao T, Lin Y, Wang Y, Dong C, Liu J. A field study on seasonal adaptive thermal comfort of the elderly in nursing homes in Xi'an, China. Build Environ 2022;208:108623. https://doi.org/https://doi.org/10.1016/j.buildenv.2021.108623.

[93] Fan G, Xie J, Yoshino H, Yanagi U, Hasegawa K, Kagi N, et al. Indoor environmental conditions in urban and rural homes with older people during heating season: A case in cold region, China. Energy Build 2018;167:334–46. https://doi.org/10.1016/j.enbuild.2018.01.064.

[94] Jian Y, Liu J, Pei Z, Chen J. Occupants' tolerance of thermal discomfort before turning on air conditioning in summer and the effects of age and gender. J Build Eng 2022;50:104099. https://doi.org/https://doi.org/10.1016/j.jobe.2022.104099.

[95] Jiao Y, Yu H, Wang T, An Y, Yu Y. The relationship between thermal environments and clothing insulation for elderly individuals in Shanghai, China. J Therm Biol 2017;70:28–36. https://doi.org/10.1016/j.jtherbio.2017.07.002.

[96] Tang Y, Yu H, Wang Z, Luo M, Zhang K, Jiao Y, et al. Typical winter clothing characteristics and thermal insulation of ensembles for older people in China. Build Environ 2020;182:107127. https://doi.org/10.1016/j.buildenv.2020.107127.

[97] Van Hoof J, Hensen JLM. Thermal comfort and older adults. Gerontechnology 2006;4:223–8.

[98] Li H, Xu G, Chen J, Duan J. Investigating the Adaptive Thermal Comfort of the Elderly in Rural Mutual Aid Homes in Central Inner Mongolia. Sustainability 2022;14. https://doi.org/10.3390/su14116802.

[99] Tao Y, Gou Z, Yu Z, Fu J, Chen X. The challenge of creating age-friendly indoor environments in a high-density city: Case study of Hong Kong's care and attention homes. J Build Eng 2020;30:101280. https://doi.org/10.1016/j.jobe.2020.101280.

[100] Bae C, Lee H, Chun C. Predicting indoor thermal sensation for the elderly in welfare centres in Korea using local skin temperatures. Indoor Built Environ 2017;26:1155–67. https://doi.org/10.1177/1420326x16664563.

[101] Tartarini F, Cooper P, Fleming R. Thermal environment and thermal sensations of occupants of nursing homes: A field study. Procedia Eng 2017;180:373–82. https://doi.org/10.1016/j.proeng.2017.04.196.

[102] International Organization for Standardization. ISO 7726:1998 Ergonomics of the thermal environment—Instruments for measuring physical quantities 1998.

[103] Song W, Lu Y, Liu Y, Yang Y, Jiang X. Effect of partial-body heating on thermal comfort and sleep quality of young female adults in a cold indoor environment. Build Environ 2020;169:106585. https://doi.org/10.1016/j.buildenv.2019.106585.

[104] Ministry of Housing and Urban-Rural Development of the People's Republic of China. JGJ 450-2018: Standard for design of care facilities for the aged 2018.

[105] Ministry of Housing and Urban-Rural Development of the People's Republic of China. GB 50736-2012: Design code for heating ventilation and air conditioning of civil buildings 2012.

[106] Coull NA, Hodder SG, Havenith G. Age comparison of changes in local warm and cold sensitivity due to whole body cooling. J Therm Biol 2022;104:103174. https://doi.org/10.1016/j.jtherbio.2021.103174.

[107] Guedes MC, Matias L, Santos CP. Thermal comfort criteria and building design: Field work in Portugal. Renew Energy 2009;34:2357–61. https://doi.org/10.1016/j.renene.2009.03.004.

[108] Indraganti M, Rao KD. Effect of age, gender, economic group and tenure on thermal comfort: A field study in residential buildings in hot and dry climate with seasonal variations. Energy Build 2010;42:273–81. https://doi.org/10.1016/j.enbuild.2009.09.003.

[109] Tejedor B, Casals M, Gangolells M, Macarulla M, Forcada NN. Human comfort modelling for elderly people by infrared thermography: Evaluating the thermoregulation system responses in an indoor environment during winter. Build Environ 2020;186:107354. https://doi.org/10.1016/j.buildenv.2020.107354.

[110] Jiao Y, Yu H, Wang Z, Wei Q, Yu Y. Influence of individual factors on thermal satisfaction of the elderly in free running environments. Build Environ 2017;116:218–27. https://doi.org/10.1016/j.buildenv.2017.02.018.

[111] Tweed C, Humes N, Zapata-Lancaster G. The changing landscape of thermal experience and warmth in older people's dwellings. Energy Policy 2015;84:223–32. https://doi.org/https://doi.org/10.1016/j.enpol.2015.03.011.

[112] Jiang H, Yao R, Han S, Du C, Yu W, Chen S, et al. How do urban residents use energy for winter heating at home? A large-scale survey in the hot summer and cold winter climate zone in the Yangtze River region. Energy Build 2020:110131. https://doi.org/10.1016/j.enbuild.2020.110131.

[113] Yao R, Zhang S, Du C, Schweiker M, Hodder S, Olesen BW, et al. Evolution and performance analysis of adaptive thermal comfort models – A comprehensive literature review. Build Environ 2022;217:109020. https://doi.org/10.1016/j.buildenv.2022.109020.

[114] Xiong J, Ma T, Lian Z, de Dear R. Perceptual and physiological responses of elderly subjects to moderate temperatures. Build Environ 2019;156:117–22. https://doi.org/10.1016/j.buildenv.2019.04.012.

[115] Wang Z, Yu H, Jiao Y, Chu X, Luo M. Chinese older people's subjective and physiological responses to moderate cold and warm temperature steps. Build Environ 2019;149:526–36. https://doi.org/10.1016/j.buildenv.2018.12.058.

[116] Watts AJ. Hypothermia in the aged: a study of the role of cold-sensitivity. Environ Res 1971;5:119–26.

[117] Xie J, Li H, Li C, Zhang J, Luo M. Review on occupant-centric thermal comfort sensing, predicting, and controlling. Energy Build 2020;226:110392. https://doi.org/10.1016/j.enbuild.2020.110392.

[118] Yun H, Yang J, Lee BH, Kim J, Sohn JR. Indoor thermal environment long-term data analytics using IoT devices in Korean apartments: A case study. Int J Environ Res Public Health 2020;17:1–15. https://doi.org/10.3390/ijerph17197334.

[119] Wang Z. How frequent should we measure the indoor thermal environment. Build Environ 2022;222:109464. https://doi.org/10.1016/j.buildenv.2022.109464.

[120] Li D, Menassa CC, Kamat VR. Non-intrusive interpretation of human thermal comfort through analysis of facial infrared thermography. Energy Build 2018;176:246–61. https://doi.org/10.1016/j.enbuild.2018.07.025.

[121] Yi C yoon, Childs C, Peng C, Robinson D. Thermal comfort modelling of older people living in care homes: An evaluation of heat balance, adaptive comfort, and thermographic methods. Build Environ 2022;207:108550. https://doi.org/10.1016/j.buildenv.2021.108550.

[122] Yu C, Li B, Wu Y, Chen B, Kosonen R, Kilpelainen S, et al. Performances of machine learning algorithms for individual thermal comfort prediction based on data from professional and practical settings. J Build Eng 2022;61:105278. https://doi.org/https://doi.org/10.1016/j.jobe.2022.105278.

[123] Cen C, Cheng S, Wong NH. Physiological sensing of personal thermal comfort with wearable devices in fan-assisted cooling environments in the tropics. Build Environ 2022;225:109622. https://doi.org/10.1016/j.buildenv.2022.109622.

[124] Liu S, Schiavon S, Das HP, Jin M, Spanos CJ. Personal thermal comfort models with wearable sensors. Build Environ 2019;162:106281. https://doi.org/10.1016/j.buildenv.2019.106281.

[125] Hasan MH, Alsaleem F, Rafaie M. Sensitivity study for the PMV thermal comfort model and the use of wearable ldevices biometric data for metabolic rate estimation. Build Environ 2016;110:173–83. https://doi.org/10.1016/j.buildenv.2016.10.007.

[126] Wang Z, Matsuhashi R, Onodera H. Towards wearable thermal comfort assessment framework by analysis of heart rate variability. Build Environ 2022;223:109504. https://doi.org/10.1016/j.buildenv.2022.109504.

[127] Li W, Zhang J, Zhao T, Liang R. Experimental research of online monitoring and evaluation method of human thermal sensation in different active states based on wristband device. Energy Build 2018;173:613–22. https://doi.org/10.1016/j.enbuild.2018.05.056.

[128] Kim H, Jung D, Choi H, Hong T. Advanced prediction model for individual thermal comfort considering blood glucose and salivary cortisol. Build Environ 2022;224:109551. https://doi.org/10.1016/j.buildenv.2022.109551.

[129] Li P, Dai P, Cao D, Liu B, Lu Y. Non-intrusive comfort sensing: Detecting age and gender from infrared images for personal thermal comfort. Build Environ 2022;219:109256. https://doi.org/10.1016/j.buildenv.2022.109256.

[130] Ngarambe J, Yun GY, Kim G. Prediction of indoor clothing insulation levels: A deep learning approach. Energy Build 2019;202:109402. https://doi.org/10.1016/j.enbuild.2019.109402.

[131] Choi H, Um CY, Kang K, Kim H, Kim T. Review of vision-based occupant information sensing systems for occupant-centric control. Build Environ 2021;203:108064. https://doi.org/10.1016/j.buildenv.2021.108064.

[132] Choi H, Jeong B, Lee J, Na H, Kang K, Kim T. Deep-vision-based metabolic rate and clothing insulation estimation for occupant-centric control. Build Environ 2022;221:109345. https://doi.org/10.1016/j.buildenv.2022.109345.

[133] Kim J, Zhou Y, Schiavon S, Raftery P, Brager G. Personal comfort models: Predicting individuals' thermal preference using occupant heating and cooling behavior and machine learning. Build Environ 2018;129:96–106. https://doi.org/10.1016/j.buildenv.2017.12.011.

[134] Dai C, Zhang H, Arens E, Lian Z. Machine learning approaches to predict thermal demands using skin temperatures: Steady-state conditions. Build Environ 2017;114:1–10. https://doi.org/10.1016/j.buildenv.2016.12.005.

[135] Kim J, Schiavon S, Brager G. Personal comfort models – A new paradigm in thermal comfort for occupant-centric environmental control. Build Environ 2018;132:114–24. https://doi.org/10.1016/j.buildenv.2018.01.023.

[136] Jiang L, Yao R. Modelling personal thermal sensations using C-Support Vector Classification (C-SVC) algorithm. Build Environ 2016;99:98–106. https://doi.org/10.1016/j.buildenv.2016.01.022.

[137] Qavidel Fard Z, Zomorodian ZS, Korsavi SS. Application of machine learning in thermal comfort studies: A review of methods, performance and challenges. Energy Build 2022;256:111771. https://doi.org/10.1016/j.enbuild.2021.111771.

[138] Luo M, Xie J, Yan Y, Ke Z, Yu P, Wang Z, et al. Comparing machine learning algorithms in predicting thermal sensation using ASHRAE Comfort Database II. Energy Build 2020;210:109776. https://doi.org/10.1016/j.enbuild.2020.109776.

[139] Zhou X, Xu L, Zhang J, Niu B, Luo M, Zhou G, et al. Data-driven thermal comfort model via support vector machine algorithms: Insights from ASHRAE RP-884 database. Energy Build 2020;211:109795. https://doi.org/10.1016/j.enbuild.2020.109795.

[140] Zhang J, Liu H, Wu Y, Zhou S, Liu M. Neural network-based thermal comfort prediction for the elderly. E3S Web Conf 2021;237:1–5. https://doi.org/10.1051/e3sconf/202123702022.

[141] Arakawa Martins L, Soebarto V, Williamson T. Performance evaluation of personal thermal comfort models for older people based on skin temperature, health perception, behavioural and environmental variables. J Build Eng 2022;51:104357. https://doi.org/https://doi.org/10.1016/j.jobe.2022.104357.

[142] Arakawa Martins L, Soebarto V, Williamson T, Pisaniello D. Personal thermal comfort models: a deep learning approach for predicting older people's thermal preference. Smart Sustain Built Environ 2022;11:245–70. https://doi.org/10.1108/SASBE-08-2021-0144.

[143] Bennetts H, Arakawa Martins L, van Hoof J, Soebarto V. Thermal personalities of older people in south Australia: A personas-based approach to develop thermal comfort guidelines. Int J Environ Res Public Health 2020;17:8402. https://doi.org/10.3390/ijerph17228402.

[144] De Lepeleire J, Bouwen A, De Coninck L, Buntinx F. Insufficient lighting in nursing homes. J Am Med Dir Assoc 2007;8:314–7. https://doi.org/10.1016/j.jamda.2007.01.003.

[145] Chen Y, Fan J, Zhou T. A theoretical approach for therapeutic artificial supplementary lighting in elderly living spaces. Build Environ 2021;197:107876. https://doi.org/10.1016/j.buildenv.2021.107876.

[146] Panraluk C, Sreshthaputra A. Developing guidelines for thermal comfort and energy saving during hot season of multipurpose senior centers in Thailand. Sustainability 2020;12. https://doi.org/10.3390/SU12010170.

[147] Younes J, Chen M, Ghali K, Risto K, Melikov AK, Ghaddar N. A thermal sensation model for elderly under steady and transient uniform conditions. Build Environ 2022;227:109797. https://doi.org/10.1016/j.buildenv.2022.109797.

[148] Davoodi F, Hasanzadeh H, Alireza Zolfaghari S, Maerefat M. Developing a new individualized 3-node model for evaluating the effects of personal factors on thermal sensation. J Therm Biol 2017;69:1–12. https://doi.org/10.1016/j.jtherbio.2017.05.004.

[149] Davoodi F, Hassanzadeh H, Zolfaghari SA, Havenith G, Maerefat M. A new individualized thermoregulatory bio-heat model for evaluating the effects of personal characteristics on human body thermal response. Build Environ 2018;136:62–76. https://doi.org/10.1016/j.buildenv.2018.03.026.

[150] Guergova S, Dufour A. Thermal sensitivity in the elderly: A review. Ageing Res Rev 2011;10:80–92. https://doi.org/10.1016/j.arr.2010.04.009.

[151] Dorfman LJ, Bosley TM. Age-related changes in peripheral and central nerve conduction in man. Neurology 1979;29:38–44. https://doi.org/10.1212/wnl.29.1.38.

[152] Jiang Y, Wang Z, Lin B, Mumovic D. Development of a health data-driven model for a thermal comfort study. Build Environ 2020;177:106874. https://doi.org/10.1016/j.buildenv.2020.106874.

[153] Gasparrini A, Guo Y, Hashizume M, Lavigne E, Zanobetti A, Schwartz J, et al. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. Lancet 2015;386:369–75. https://doi.org/10.1016/s0140-6736(14)62114-0.

[154] The Ministry of Social Affairs and Health of Finland. Decree of the Ministry of Social Affairs and Health: the health conditions of the dwelling and other living area, as well as the qualifications of external experts 2015. https://www.finlex.fi/fi/laki/alkup/2015/20150545#Pidm45053757573872 (accessed February 1, 2023).

[155] Kollanus V, Tiittanen P, Lanki T. Mortality risk related to heatwaves in Finland – Factors affecting vulnerability. Environ Res 2021;201. https://doi.org/10.1016/j.envres.2021.111503.

[156] Karyono K, Abdullah BM, Cotgrave AJ, Bras A. The adaptive thermal comfort review from the 1920s, the present, and the future. Dev Built Environ 2020;4:100032. https://doi.org/https://doi.org/10.1016/j.dibe.2020.100032.