Thermal demand characteristics of elderly people with varying levels of frailty in residential buildings during the summer

Haixia Zhou[a, b], Wei Yu[a, b, *], Keyao Zhao[a, b], Hanyu Shan[a, b], Shan Zhou[a, b], Shen Wei[c], Linyuan Ouyang[a, b]

[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, China

[c] The Bartlett School of Sustainable Construction, University College London (UCL), 1-19 Torrington Place, London WC1E 7HB, United Kingdom

Corresponding author at Joint International Research Laboratory of Green Buildings and Built Environments (Ministry of Education), Chongqing University, Chongqing 400045, China. E-mail address: yuweicqu@cqu.edu.cn (W. Yu).

Abstract

As society ages, there is a growing concern for the comfort and health of elderly people. Differences in the degree of physiological aging in the elderly population lead to possible differences in their ability of adapting to environmental changes to maintain thermal comfort. To verify such differences in thermal environmental demands due to aging and physiological function changes, this study has used Fried's frailty classification method in combination with a wristband device for a field survey of 394 elderly people in residential buildings in Chongqing, China. The study was carried out in the summer and measured participants' both psychological and physiological responses. The study result showed that frailer elderly people had higher thermal sensitivity and a narrower range of comfortable temperatures. The neutral temperature was identified to be 25.8℃ for non-frailty people, 26.9℃ for pre-frailty people, and 27.9℃ for frailty people, with comfort temperature intervals of 24.0℃ to 30.0℃ for non-frailty people, 24.3℃ to 29.3℃ for pre-frailty people and 25.9℃ to 29.3℃ for frailty people. In terms of physiological regulation, frail elderly people showed lower sweating rates (SI) and pulse intensity (PI), with higher heart rates (HR) in summer. The study provides evidence that the frailty of physiological functions has an innegletable impact on elderly people's thermal demand, so when designing indoor thermal environment for them their frailty condition needs to be properly considered.

Keywords: elderly people, thermal demand, frailty, neutral temperature, physiological regulation

1 Introduction

Nowadays, population aging has become a global trend. Generally, it is commonly accepted that people aged 65 and over can be considered as elderly people [1–3], and it has been predicted that by 2050 this population will approach 1.5 billion [4]. Elderly people spend about 80% of their time indoors [5,6]. Additionally, compared to other aging groups, their immune system and physiological regulation are often weaker [7–9]. During heat waves, impaired physiological responses for maintaining homeostasis during heat exposure can lead to increased risk of health disorders in elderly people [3]. Therefore, providing a comfortable and healthy indoor environment for them becomes more important.

Many studies have given concerns about the environmental conditions elderly people are living in [1,10–17]. These studies have been carried out in both real buildings, such as nursing homes [10,13,18–21] and residential buildings [2,20,22–24] and laboratory environments [1,12,25]. In existing studies, many researchers have identified a significant difference in the thermal comfort requirements between adults and elderly people, so age has been widely accepted as an influential factor in thermal comfort [1,12,26–30]. Additionally, elderly people have been further classified into sub-categories with different thermal comfort requirements using common factors like climatic zones [10,18,20,31–33], seasons [18,19], age [13,34], and gender [31,35], and these classifications give more tailored and accurate control of indoor thermal comfort for elderly people. For example, Zheng et al. [10] found different neutral temperatures (T_n) between elderly people living in Xi'an (Cold climate zone) and Shanghai (Hot Summer and Cold Winter climate zone), China. In Korea, Yang et al. [18] studied the effect of seasonal characteristics on elderly people’s thermal comfort and identified significantly higher T_n in the cooling season than in other seasons. About age, Zheng et al. [34] have proposed a further age classification for elderly people, namely, [60-69], [70-89], and [90-99], to provide more accurate reflection of their thermal comfort requirement. Between males and females, Forcada et al. [31] identified different T_n and preferred temperatures.

In real life, it has been observed that elderly individuals with different levels of health have varying requirements for their thermal environment, despite sharing the same age. Some scholars, especially those in medical science, believe that the physical impairments and pathophysiological states of elderly people can increase their risk in extreme weather [3,36]. Therefore, the obsolete concept of "chronological age" is being replaced by a more accurate and person-tailored parameter, i.e. "biological age", to better reflect their physiological state [3,9,37]. This biological age for elderly people is often expressed by the level of frailty [38], which indicates the level of an individual's physiological state, not disability [39]. Frailty is considered to be a geriatric syndrome [38], and it is a complex mechanism of aging including the accumulated functional decline of multiple physiological systems, independent of age [39]. The main organ systems involved in the development of frailty include brains, endocrine systems, immune systems, and skeletal muscles [39], and the main physiological thermal defenses of the human body for heat are vasodilation and sweating, and for cold they are skin vasoconstriction and heat production without shivering [40]. Peripheral thermoregulatory systems, central thermoregulatory systems, and temperature-activated transient receptor potential (TRP) all affect the human body's thermal regulation [41], and the functions of all these systems may be affected by frailty. For example, a frail endocrine system can affect the secretion of key circulating hormones by the hypothalamus (e.g. stress regulation) [42] and a frail brain can cause the decline of cognition for elderly people (e.g. heat perception) [43]. However, until now, there is still lack of understanding on the effect of frailty on elderly people's thermal comfort requirements.

To fill the aforementioned gap of research, this study combined non-invasive devices and subjective questionnaires to study the effect of frailty on elderly people's thermal comfort requirements, using field-measured data from 394 elderly people living in Chongqing, China, hoping to justify the importance of including frailty level to decide the thermal comfort requirements of elderly people. The second chapter of this paper describes the research methodology adopted in this study. The third chapter explains the main findings from the data analysis. The fourth chapter discussed the thermal comfort and physiological regulation under levels of frailty. The last chapter then gives a summary of the whole paper.

2 Research Methodology

This study was primarily designed based on the hypothesis that there may be a relationship between frailty and thermal demand. The hypothesis was tested by utilizing field research experience in thermal comfort and frailty grading methods. The specific research framework is illustrated in Figure 1 throughout the entire manuscript.

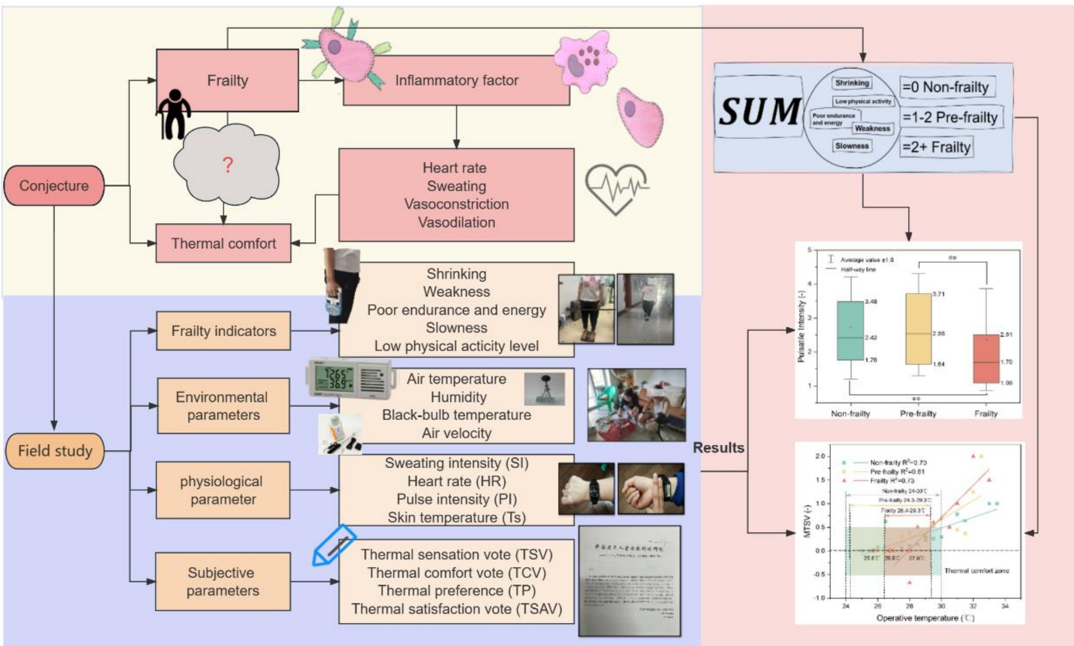


Figure 1. Research framework

2.1 Research design

To understand indoor thermal comfort, physiological regulation parameters, and behavioral habits of elderly people, a field survey was conducted between 10th July to 15th September (summer time), 2022, in Chongqing, China. According to the Chinese standard of GB 50352-2019 [44], Chongqing has a local climate classified as Hot Summer and Cold Winter (HSCW). In the survey, 394 elderly people were visited in their homes, which are located in a total number of 58 buildings. Figure 2 has indicated the distribution of these buildings in Chongqing, with some representative buildings highlighted. Considering the poor eyesight of most elderly people, the questionnaire survey was mainly done in an ask (researcher)-and-answer (participant) mode. All participants are over 65 years old, and without severe diabetes or cancer issues [3]. As this study involved vulnerable people, before starting the survey, relevant ethical approval has been obtained from the Ethical Committee for Life Sciences, Central China Normal University, as well as relevant consent from the participants. Table 1 has listed some basic statistics about the participants of this study.

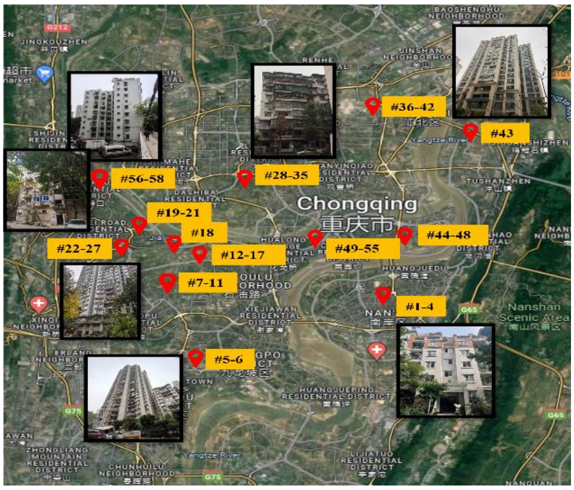


Figure 2. Distribution of investigated residential buildings in the study

For the 394 participants of this study, 4.57% are living alone, 61.68% are living with their partner, 22.33% are living with their children only, and 11.42% are living with both their partner and children. The study was carried out in the participants' homes, involving the collection of both objective data (physical and physiological parameters), subjective data (thermal sensations and preferences), and frailty-relevant information, as shown in Figure 3a. To ensure test stability, the survey time for each elderly person was kept for about 30 minutes [20]. Moreover, during the survey period, they were required to remain in a low-activity state (seated position) at home, and thus, the metabolic rate was considered to be consistent (1 met). And, the clothing insulation of the elderly was recorded, including their tops, trousers, skirts, footwear, chairs, etc. Their overall clothing insulation during the summer at home was found to be low, with an average value of 0.31 and a standard deviation of 0.09.

Table 1. Sample characteristic distribution

	Age [34]			**Gender**	
Characteristic	65-69	70-89	Over 89	Male	Female
Sample	158	233	3	169	225
Percentage	40%	59%	1%	43%	57%

(a) Questionnaires and monitoring (b) Physiological parameter measurements

Figure 3. Field measurements

2.2 Objective data collection

2.2.1 Environmental parameters

During the study, major environmental parameters, including air temperature, humidity, black-bulb temperature, and air velocity, were measured by laboratory-level equipment, and Table 2 has listed their main specifications.

Table 2. Measurement instrument specifications

Parameter	Brand/Model	Equipment	Range	Accuracy
Air Temperature	UX100-003	HOBO automatic temperature and humidity data collector	-20°C ~ 70°C	±0.2°C
Humidity	UX100-003	HOBO automatic temperature and humidity data collector	1% ~ 95%	±3%
Black-bulb temperature	HQZY-1	Automatic black-bulb ball temperature recording instrument	-20°C ~ 80°C	±0.3°C
Air velocity	WWFWZY-1	Universal anemometer	0.05~30m/s	0.01m/s

2.2.2 Physiological parameters

The study also collected some major physiological parameters, namely sweating intensity (SI), heart rate (HR), pulse intensity (PI, the size of the blood flow volume), and skin temperature (T_s), from each participant by a wristband device Biovital-P1, as shown in Figure 3b. In humans, the autonomous (or physiological) thermal defense is vasodilation of the skin and sweating [40]. It has been suggested that in thermoregulation, skin vasodilation (increased blood flow) and sweating are weakened in the elderly [45,46]. Some scholars believe that the increase in cardiac output decreases and the maximum HR decreases during heat stress in the elderly, suggesting that HR may also differ from the pattern of change in younger people [3]. At the same time, the T_s of hands can effectively predict the thermal sensation of the elderly [24,47,48].

Using the wristband device, T_s and HR can be directly measured, while the SI needs to be derived from the ratio of change in skin impedance to time, and the PI needs to be derived indirectly from the photoplethysmography (PPG) waveform graph [49]. To ensure scientific validity, the device was pre-tested and calibrated before the measurements. Table 3 has listed the sample rate and the accuracy for each physiological parameter. To ensure good accuracy, the participants were asked to move their arms as little as possible during the experiment [50].

Table 3. Wristband specifications

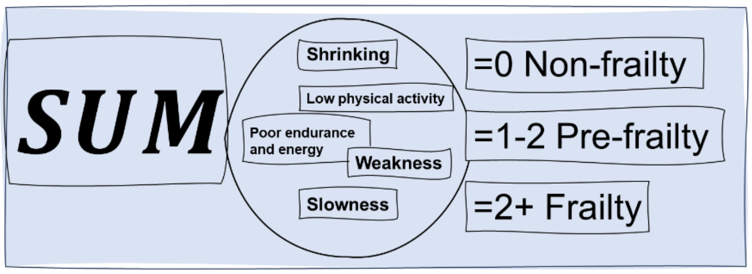
Parameters	Sampling rate	Accuracy
PPG (Pulsation intensity and heart rate)	25HZ	3bpm
Skin impedance (Sweating intensity)	4HZ	0.01μs
Skin temperature	1HZ	0.1°C

2.3 Subjective data collection

The questionnaire contains some basic information about the participants, such as their age, address, contact information and building condition. It also includes their thermal sensation vote (TSV), thermal comfort vote (TCV), thermal preference (TP), and thermal satisfaction vote (TSAV). The TSV was assessed using the ASHRAE seven-point thermal sensation scale (-3 cold, -2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot) [51]. The TP uses a 3-level scale: -1 cooler, 0 unchanged, 1 warmer. The TCV was assessed using the four-point thermal comfort scale (0 comfortable, +1 slightly comfortable, +2 uncomfortable, +3 unbearable) [52]. The TSAV was evaluated using a seven-point scale(-3 very unsatisfied, -2 dissatisfied, -1 slightly dissatisfied, 0 acceptable, +1 slightly satisfied, +2 satisfied, +3 very satisfied) [20,53].

2.4 Calculation of frailty level

According to Dent [54], a popular and simple method that can be used to define the frailty level of elderly people is frailty phenotypic [37,55], especially the one developed by Fried et al. [55]. This method adopts five phenotypic indicators relating to the physical health and the metabolism of elderly people, and they are 1) shrinking: unintentional weight loss at least 4.5 kg in the past year, 2) weakness: grip strength in the lowest 20% at baseline, adjusted for gender and body mass index, 3) poor endurance and energy: identified by two questions from the Spanish version [56] of the modified 10-item Center for Epidemiological Studies-Depression (CES-D) scale [57], 4) slowness: the slowest 20% at baseline, based on time to walk 15 ft, adjusting for gender and standing height, and 5) low physical activity level: the lowest 20% at baseline, based on a weighted score of kilocalories expended per week, calculated according to the Spanish validation [58] of the Minnesota Leisure Time Activity questionnaire [59] according to each participant’s report, and adjusting for gender [55,60]. In this study, questionnaires were used to collect information on five indicators, which included measurements of participants' height, weight, grip strength, and walking speed, as well as their self-reported levels of fatigue and daily exercise. Participants' physical indicators were measured as shown in Figures 4b, 4c and 4d. The level of frailty was then defined according to the number of occurrences of these indicators. Non-frailty is defined when none of the indicators are present. Pre-frailty is defined when one or two indicators are present, and frailty is defined when three or more indicators are present [55], as shown in Figure 4a.



(a) Calculation of frailty levels

(b) Grip strength (c)Weight and height (d) Walking speed

Figure 4. Calculation and measurement of physical indicators

2.5 Data analysis methods

In this study, the data analysis was carried out in SPSS 23 for significance determination. Analysis of Variance (ANOVA), chi-square test, and K-W test have been used to analyze the significance of the difference between different physiological and environmental parameters in the frailty levels, and Pearson correlation analysis has been used to analyze the relationship between operative temperature (t_{op}) and different physiological parameters. To quantify the relationship between the parameters mean thermal sensation vote (MTSV) and t_{op}, SI and t_{op}, PI and t_{op}, TCV and TSV, linear regression was used, with a significance level set as 0.05. To evaluate the goodness-of-fit of the linear model, the R^2 value was adopted. Additionally, linear regression of MTSV and T_{op} can calculate the neutral temperature (T_n), which represents participants' 'neutral' perception of thermal sensation [61].

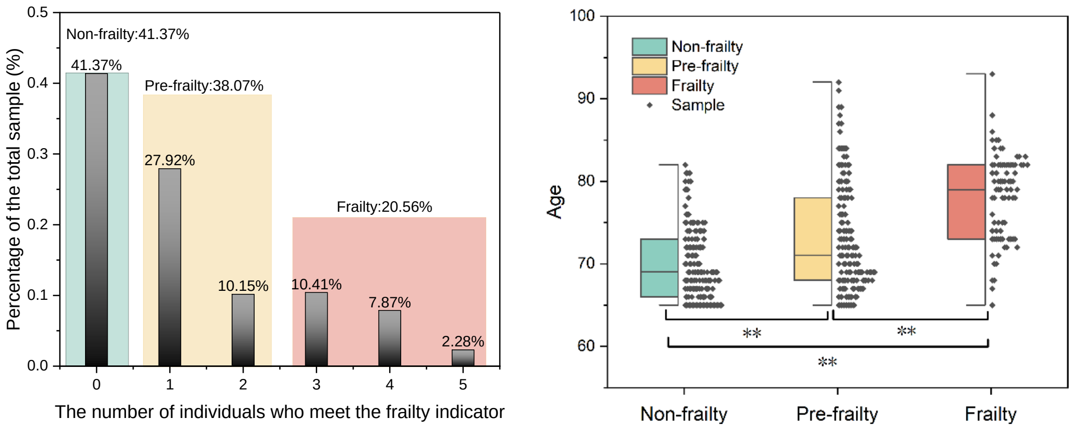
3 Results

3.1 Basic information about the survey

3.1.1 Classification of frailty levels

The 394 elderly individuals examined were characterized utilizing the method for determining the level of frailty described in section 2.4. The proportions of elderly individuals meeting different numbers of indicators and frailty levels are depicted in Figure 5a, with the distribution chart being displayed. Among them, the non-frail category includes 41.37% of elderly individuals who do not meet any indicators. The pre-frail category comprises 38.07% in total, with 27.92% meeting 1 indicator and 10.15% meeting 2 indicators. The frail category consists of 20.56% in total, with 10.41%, 7.87%, and 2.28% meeting 3, 4, and 5 indicators, respectively. The low rate of frailty found in the study may be attributed to the fact that most elderly individuals residing in residential buildings are in better health and frail elderly people are oftentimes reluctant to participate in research activities.

Given that the age of the elderly participants did not adhere to a normal distribution, K-W tests and pairwise comparisons were conducted to explore differences in frailty categories across different age groups. The significant differences among different age groups can be observed in Figure 5b, with higher age groups being more likely to be classified as frail. However, it is crucial to recognize that although age and frailty level are positively correlated, age alone cannot strictly define a person's level of frailty, which elucidates the distinct age ranges for each frailty category.



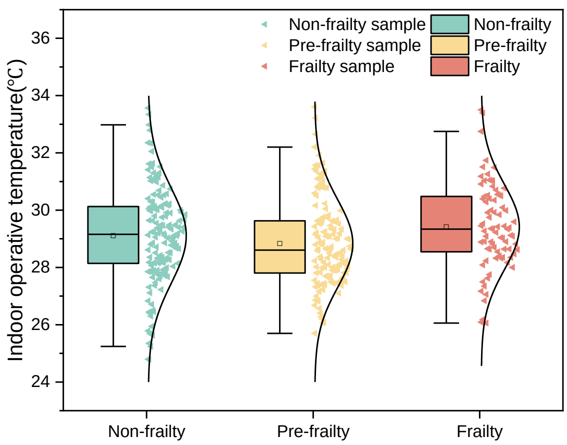
(a) The distribution of proportions for different frailty levels and numbers of indicators

(b) Age distribution of different frailty levels

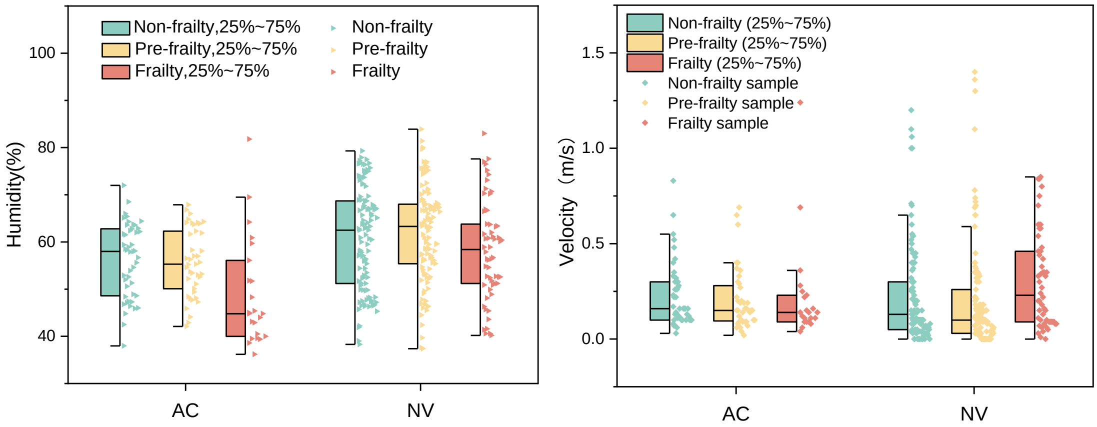
Figure 5. Frailty statistics

3.1.2 Indoor thermal environment

Observations made on the indoor temperature distribution, as presented in Figure 6a, indicated that elderly individuals classified as non-frailty, pre-frailty, and frailty had similar upper and lower quartile ranges for preferred temperatures between 28.0-30.0°C. To identify significant differences in temperature preference among elderly individuals with different frailty levels, a K-W test was conducted and found to be significant ($p=0.004$). Further pairwise comparisons revealed significant differences in terms of air temperature between non-frail and pre-frail elderly individuals ($P=0.33$), as well as between non-frail and pre-frail elderly individuals ($P=0.07$). Further pairwise comparisons revealed significant differences in terms of ANOVA and K-W tests conducted on wind speed and humidity environments for elderly individuals with different frailty levels and operating in different modes (air conditioning (AC) and natural ventilation (NV)) did not yield any significant differences. However, observations made from Figure 6b and Figure 6c revealed that humidity and wind speed were higher in NV environments compared to AC environments.



(a) Air temperature



(b) Humidity (c) Air velocity

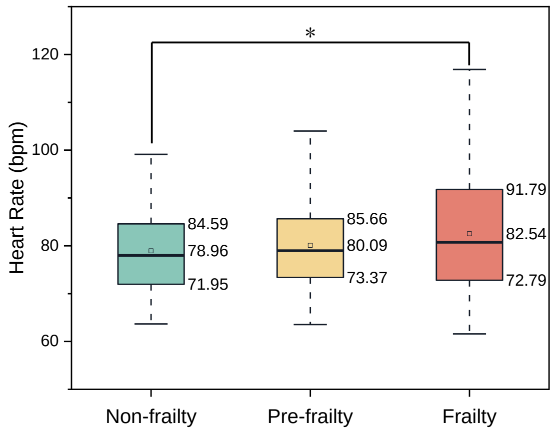
Figure 6. Indoor environmental parameters distribution for different frailty levels

3.2 Physiological characteristics of the elderly

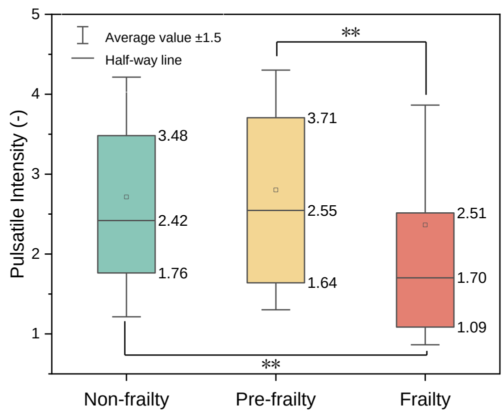
3.2.1 Physiological parameters and frailty levels

The HR, PI, SI and T_s distribution did not satisfy normality assumptions and hence, the K-W test was used. Among these parameters, no significant differences were found between frailty levels for Ts. However, significant differences were observed for HR (p=0.025), PI (p=0.000), and SI (p=0.001), between frailty levels. The distribution of physiological parameters and frailty levels can be seen in Figure 7. For the PI, HR, and SI measures, pairwise comparisons were conducted. It was found that there were significant differences in HR between the non-frail and frail elderly individuals (p=0.20). The median HR for frailty elderly individuals was 82.58 bpm, 80.09 bpm for pre-frailty, and 78.96 bpm for non-frailty, as demonstrated in Figure 7a. In terms of PI, significant differences were observed between the non-frail and frail elderly individuals (p=0.000), as well as between the pre-frail and frail elderly individuals (p=0.000). The median PI for frailty elderly individuals was 2.42, 2.55 for pre-frailty, and 1.70 for non-frailty (The numerical value of PI has no practical meaning and can only represent its magnitude), as demonstrated in Figure 7b. Regarding SI, significant differences were found between the non-frail and frail elderly individuals (p=0.001). The median SI for frailty elderly individuals was 49.46, 37.30 for pre-frailty, and 19.94 for non-frailty

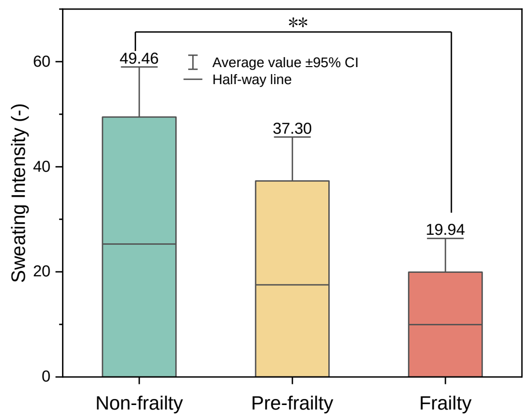
(The numerical value of SI has no practical meaning and can only represent its magnitude), as demonstrated in Figure 7c. The above information indicates that different levels of frailty have a significant impact on elderly individuals' physiological parameters.



(a) HR



(b) PI



(c) SI

Figure 7. Distribution of physiological parameters and frailty levels

3.2.2 Environmental parameters and physiological parameters

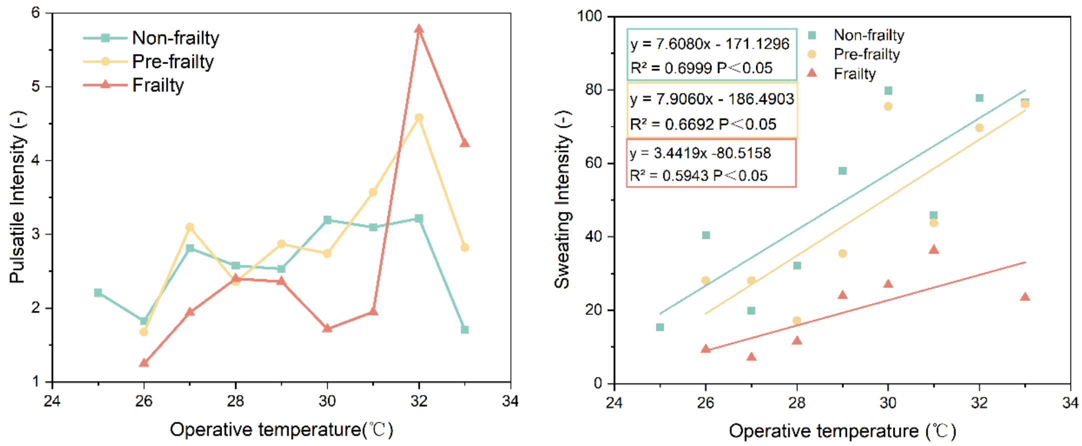
To validate the relationship between environmental parameters and physiological parameters, Pearson correlation analysis was conducted to examine the correlations of HR, PI, SI and T_s with T_{op}. The results revealed a significant correlation between PI (P=0.010), SI (P=0.000) and T_s (P=0.000) with T_{op}, whereas no correlation was observed between HR and T_{op}, as shown in Table 4, which is consistent with prior research findings [20,49]. In this section, the analysis focused solely on the fitting of the parameters PI and SI related to frailty with T_{op} (1°C interval). The average value of each parameter (PI or SI) was adopted within each interval to represent the magnitude of that parameter for that interval. as depicted in Figure 8.

Table 4. Results of correlation analysis between physiological parameters and T_{op}

Physiological parameter	HR	T_s	SI	PI
Correlation coefficient	0.077	0.285**	0.223**	0.132**
P value	0.137	0.000	0.000	0.010

** $P < 0.01$

As shown in Figure 8a, the PI for three levels of frailty increased with an increase in T_{op}. PI exhibited an enhanced trend at around 27-28℃, followed by a significant increase at approximately 32℃, and then a sharp decline. Wooyoung Jung et al. [49] also reached similar conclusions regarding video quantification of thermoregulation in young individuals. Lindberg et al. [62] also confirmed that an increase in sweat content severely affects the photoplethysmography (PPG) signal captured by the photoelectrometers. When the temperature exceeds 31-32°C, the body produces a significant amount of sweat. The increase in sweat volume for frail elderly individuals is relatively small, resulting in a minimal impact on the PI. However, non-frail elderly individuals experience a larger increase in sweat volume, leading to a greater impact on the PI. Therefore, after 32℃, there is a situation where the PI for frail elderly individuals is higher than that for non-frail elderly individuals. The PI before 32℃ reflects the true response of elderly individuals.



(a) PI (b) SI

Figure 8. Linear regression with T_{op}

The linear regression of SI with T_{op} for elderly individuals at different levels of frailty is shown in Figure 8b. From the graph, it can be observed that the SI for non-frail elderly individuals is slightly higher than that of pre-frail individuals, while both non-frail and pre-frail individuals have significantly higher SI values compared to frail individuals. Although the SI increases with an increase in T_{op} for all three levels of individuals, the rates of increase differ. The slope of SI for frail individuals is noticeably smaller than the other two levels of individuals. In a regression model of SI and T_{op}, the slope can represent the magnitude of the elderly person's ability to regulate sweating in response to temperature changes. The higher the slope the greater the regulation ability. In this study, the non-frailty and pre-frailty elderly had similar regulatory capacities, while the frailty elderly had significantly lower regulatory capacities.

3.3 Thermal comfort requirements of the elderly

3.3.1 The elderly's votes on thermal environments

The K-W test was conducted to examine TSV and TP, while the chi-square test was used to assess TSAV. The results revealed no significant differences among elderly individuals at different levels of frailty in terms of TSV, TP, and TSAV. This indicates that elderly in residential buildings exhibit similar levels of TSV, TP, and TSAV.

From the TSV distribution in Figure 9a, it can be observed that elderly individuals tend to vote more for the neutral and slightly warm options during the summer, indicating their preference for being in a neutral or slightly warm environment. In the TP graph in Figure 9b, it was found that almost all elderly individuals desire temperature to remain consistent or decrease. However, individuals at different levels of frailty have varying expectations regarding temperature reduction. Frail individuals are more inclined to expect a decrease in the overall outdoor climate rather than relying on artificial cooling sources. On the other hand, non-frail and pre-frail individuals prefer temperature reduction through a combination of climate conditions and the assistance of cooling devices. In terms of TSAV, approximately 90% of all elderly individuals are satisfied with their environment, as shown in Figure 10. This could be attributed to the greater control they have over their living conditions in residential buildings, allowing them to maintain their preferred environment for longer durations. However, this differs for elderly individuals residing in nursing homes, as they require more professional care [31]. Some individuals may experience dissatisfaction due to the influence of their children or partners, but they can find ways to alleviate this suboptimal state, such as adding layers of clothing or requesting a room change.

It is noteworthy that despite the wide range of indoor temperature distribution in the summer, the thermal comfort status of the elderly mostly remains satisfactory. This may be due to their tendency to prioritise cost reduction and energy conservation, and to achieve a satisfactory level of comfort as long as the environmental conditions are not excessively harsh.

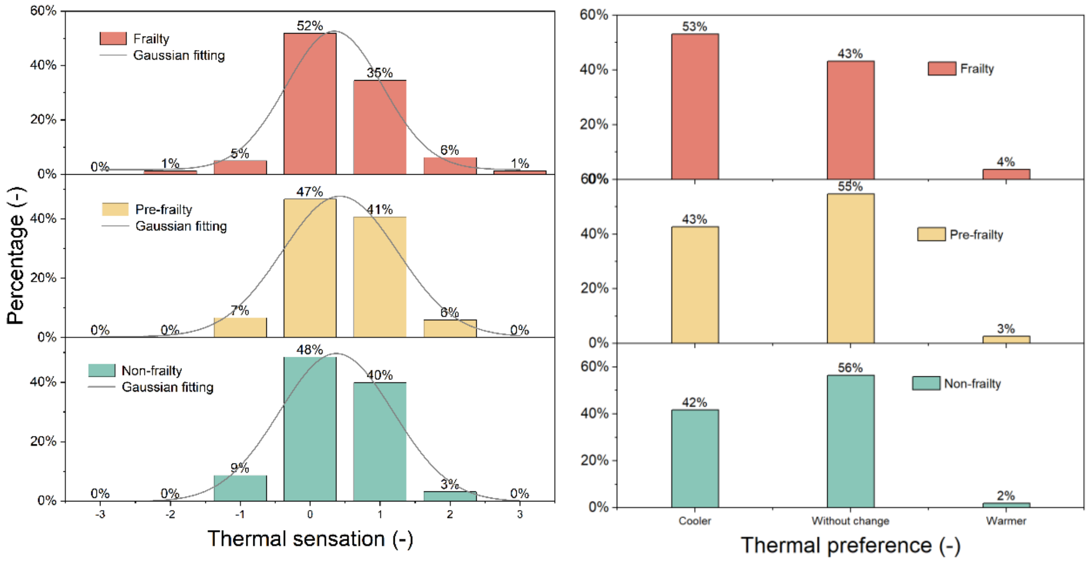


Figure 9. Thermal sensation and thermal preference distribution

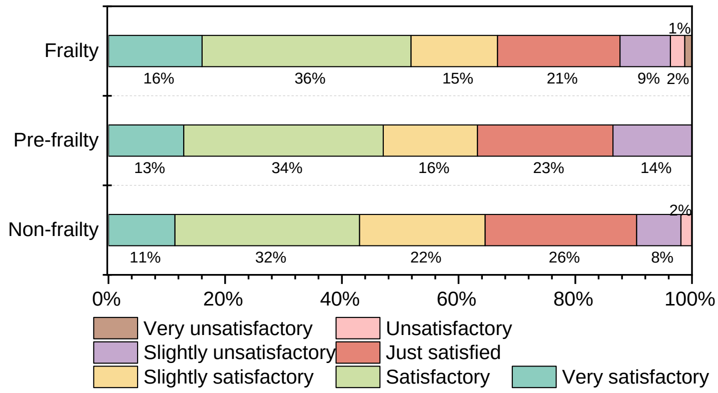


Figure 10. Environmental satisfaction distribution of elderly people

3.3.2 Thermal comfort characteristics for different levels of frailty

Thermal sensitivity and T_n can be obtained by linear regression of TSV and T_{op} [63]. Through linear regression, the T_n was calculated for the elderly with different levels of frailty as a function of their MTSV and the T_{op} with weighted 0.5°C binned data[14,20,32,64–66] (Equations 1, 2, and 3). Figure 11 presents a linear regression plot of MTSV in elderly individuals with various levels of frailty. Results show that T_n was 25.8°C in non-frailty elderly, 26.9°C in pre-frailty elderly, and 27.9°C in frailty elderly individuals. The slopes of MTSV were 0.1139 for non-frailty, 0.2001 for pre-frailty, and 0.3399 for frailty, respectively, of the elderly. The elderly population had lower thermal sensitivity slopes than adults; a lower slope indicates lower thermal sensitivity

[20,31,32,67]. Furthermore, the more frail the elderly individual, the greater the sensitivity, with close sensitivities to adults (slope of 0.35) being observed in the frailty elderly individuals [32].

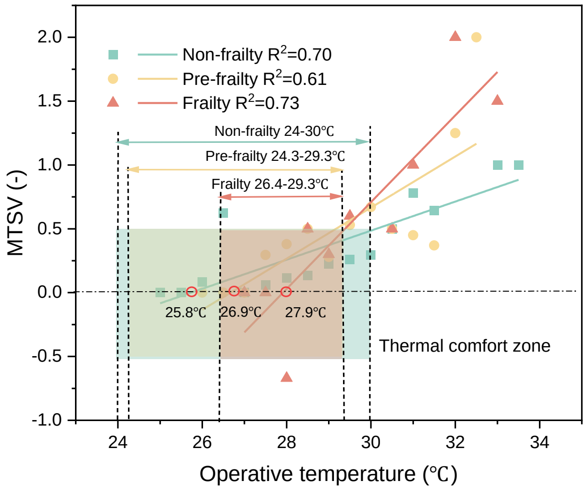


Figure 11. Linear regression plots of thermal sensory voting in elderly with different degrees of frailty

The MTSV and T_{op} regression model equations are as follows,

For non-frailty:

$$MTSV = 0.11385 * T_{OP} - 2.9297 \ (R^2 = 0.7010, P = 0.00) \quad [1]$$

For pre-frailty:

$$MTSV = 0.20011 * T_{OP} - 5.33714 \ (R^2 = 0.6134, P = 0.00) \quad [2]$$

For frailty:

$$MTSV = 0.33989 * T_{OP} - 9.48766 \ (R^2 = 0.73244, P = 0.00) \quad [3]$$

According to ASHRAE [51] standard, the thermal comfort zone is defined as the temperature range in which at least 80% of users are satisfied with the thermal environment. Additionally, ASHRAE recommends that the comfort interval for the elderly should be at least 90% due to their special needs [51,68]. This study also used 90% as the comfort temperature interval for the elderly. By using the regression model represented by Equations 1, 2, and 3, the comfort temperature intervals for the elderly with three frailty levels were determined as follows: non-frailty is 21.3℃ to 30.1℃, pre-frailty is 24.3℃ to 29.3℃, and frailty is 26.4℃ to 29.3℃. According to the Chinese standard GB/T 50785 [69], in HSCW regions in China, when the clothing insulation is 0.5 clo and TSV=-0.5, T_{min}=24.0℃and T_{max}=30.0℃. Therefore, for non-frail elderly individuals, the lower temperature limit is set at 24.0℃ and the upper limit temperature is 30.0℃, as shown in the thermal comfort zone in Figure 11. Therefore, it can be concluded that there are significant differences in the lower limit temperature under low clothing insulation during summer season among elderly individuals with different levels of frailty. The frailer the elderly person, the less resistant they are to lower temperatures in summer.

Figure 12 shows the relationship between TSV and TCV for the elderly representing different frailty levels. The relationship between the quadratic polynomial fitting curves of thermal sensation and thermal comfort was obtained as follows, respectively [70].

For non-frailty:

$$TCV = 0.2707 - 0.6168 * TSV + 1.003 * TSV^2 \ (R^2 = 0.7806, P < 0.05,) \quad [4]$$

For pre-frailty:

$$TCV = 0.2262 - 0.0923 * TSV + 0.4921 * TSV^2 \ (R^2 = 0.6541, P < 0.05) \quad [5]$$

For frailty:

$$TCV = 0.1417 - 0.0238 * TSV + 0.4775 * TSV^2 \ (R^2 = 0.9808, P < 0.05) \quad [6]$$

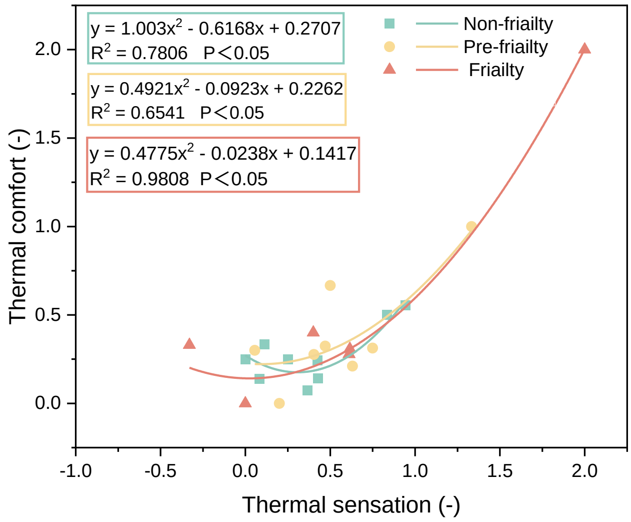


Figure 12. The relationship between TSV and TCV in elderly with different levels of frailty

Based on Equations 4, 5, and 6, it can be observed that as the TSV increases or decreases, the TCV gradually increases. The extreme values of the quadratic-linear model for the three frailty levels are non-frailty (0.3074, 0.1758), pre-frailty (0.0938, 0.2219), and frailty (0.0249, 0.2706), indicating that elderly individuals prefer neutral-warm ambient temperatures in summer. In addition, as depicted in Figure 12, it is evident that in a hot summer environment, non-frail and pre-frail elderly individuals do not experience coldness, while frail elderly individuals do. Additionally, when it comes to expressing dissatisfaction with hot, frail elderly individuals tend to have a higher level of complaints than pre-frail individuals, and pre-frail individuals have a higher level of complaints compared to healthy elderly individuals. It is worth noting that despite residing within a similar temperature range, these elderly individuals exhibit varying reactions. This phenomenon may be related to their lower ability to condition their bodies [9]. This also may be due to a combination of factors including lifestyle habits [71,72], economic factors [73], and the relatively healthy constitution [74] of the non-frailty elderly. Non-frail elderly individuals complain less, and they also indicate their ability to tolerate hotter environments. This is related to their experiences of not using air conditioning when they were younger. Additionally, they possess effective physiological regulation mechanisms, and they prefer utilizing their own psychological adjustments and other methods to combat high temperatures.

3.4 Thermal perception and physiological parameters

This section mainly analyzes the relationship between TSV and physiological parameters (HR, PI, SI and T_s) among elderly individuals at different levels of frailty, as shown in Figure 13.

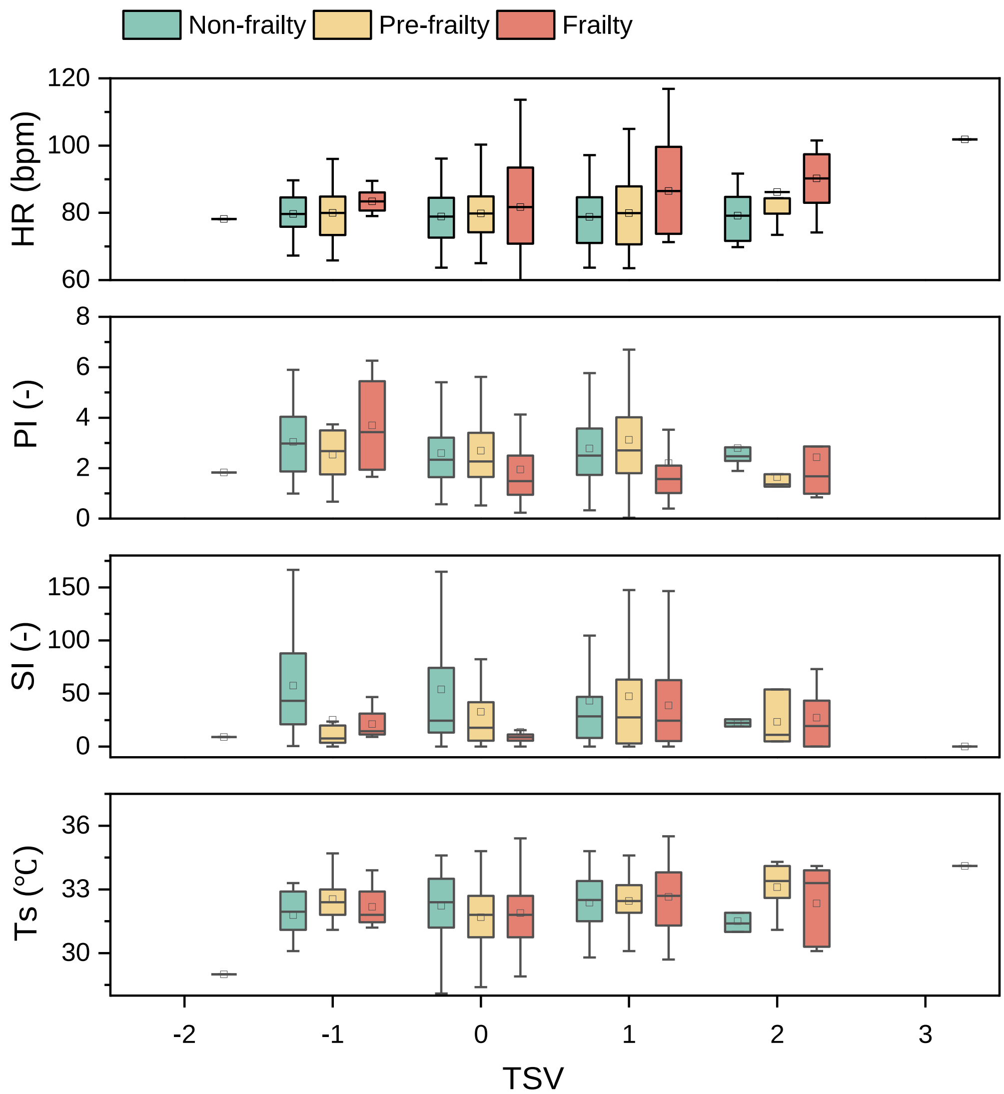


Figure 13. The relationship between TSV and physiological parameters

As the level of frailty increases and TSV increases, the HR of elderly individuals gradually increases. The PI value is easily influenced by sweating in high SI conditions, so there is a decreasing trend in TSV=2. At TSV=-2, frail elderly individuals exhibit higher PI values, whereas when TSV=1 or 2, frail elderly individuals have significantly lower PI values, indicating their weak vascular regulatory function. In terms of SI as TSV increases, the mean SI values for all elderly individuals increase, with frail elderly individuals having lower mean values. However, in terms of T_s, as TSV increases, there is a slight increase in T_s for elderly individuals, but the differences among different levels of frailty are not significant. Unlike the experimental setting, in real-life scenarios, the skin temperature of elderly individuals' hands cannot predict TSV accurately. In conclusion, the thermal perception and physiological parameters of elderly individuals mutually influence each other.

4. Discussion

4.1 The influence of physiological regulation on thermal demand

This research suggests that there are significant differences between the level of frailty in older adults and the three physiological indicators that affect thermal regulation: SI, HR, and PI. These differences may contribute to the varying heat requirements observed among older adults with different levels of frailty.

Previous studies have indicated that both total body and local sweat rate responses to passive heating decrease with age [75,76]. This is due to a decrease in dividual sweat gland output rather than in the number of actively secreting glands [46]. Such changes in sweating function may be a reasonable indicator of age-related frailty. While sweating and blood flow are regulated separately, sweat production remains dependent on adequate blood supply [46]. In this study, it was found that frail older adults have lower blood flow (represented by PI), and they also exhibit lower sweat rates. As a result, their thermal regulation ability is poorer, leading to a weaker physiological response to hot environments. This also results in a difference in thermal perception compared to non-frail elderly individuals, as they may prefer to place themselves in relatively warmer environments (within a narrower and warmer thermal comfort zone).

Similarly, HR also varies based on the frailty level. The variation in HR between different levels of frailty is probably due to the weakened functions of the aging body during thermoregulation, which requires the heart to work harder to maintain balance with the external environment as the elderly become increasingly frail. Studies suggest that as compared to younger people, the elderly experience a reduced increase in cardiac output during heat stress, which also limits the increase in cutaneous blood flow [77]. Moreover, aging results in the hardening of the central artery [78], which reduces the ability of the body cycle to respond to heat exposure [79]. This also explains why older individuals have lower PI. Additionally, stroke volume is reduced for a given left ventricular filling pressure in non-heat stressed [80]and heat-stressed conditions [77]. A study highlights that older men depend on a greater proportion of their chronotropic reserve to obtain the same HR response as the young [77], indicating that frailty elderly may have a high HR to achieve similar physiological regulation in their thermal environment as compared to pre-frailty and frailty elderly. Frailty elderly have a higher HR and limited reserves of remaining HR [71]. Therefore, they may be more likely to place themselves within narrower comfort zones.

4.2 Thermal demand characteristics

The thermal needs of elderly people vary depending on their level of frailty. In this study, the thermal need (T_n) of non-frailty elderly individuals aligned with the findings of previous studies on elderly people in Spain and Shanghai, China with T_n of 25.6°C and 25.4°C respectively [19,32]. However, the T_n of pre-frailty and frailty elderly individuals in this study were higher, by approximately 1°C and 2°C respectively, compared to non-frailty elderly individuals.

The thermal sensitivity and comfort temperature range of non-frail elderly individuals in Chongqing were found to be similar to those of elderly individuals in Shanghai [19], likely due to the shared Hot Summer and Cold Winter climate zone and the screening of only healthy elderly individuals in the Shanghai study. However, the study observed that as frailty increased, elderly individuals became more sensitive to temperature changes and had a narrower range of comfortable temperatures. Some frail elderly even expressed fear of illness associated with slightly colder indoor environments. The sensitivities of frail elderly and adults were found to be similar, but differed in their causes; adults were more dissatisfied with their environment's comfort level, while frail elderly were more fearful of illness related to environmental changes. As Slava Guergova et al. summarizes, heat pain sensations appear to be preserved in the elderly, despite age-related declines in sensitivities to non-noxious warm stimuli [81]. Due to their heightened fear of the pain caused by illness, frail older adults may psychologically reject both low and high temperatures during the summer.

The study revealed that elderly individuals with greater frailty experience a narrower comfort zone. Especially at lower temperature limits, frail elderly individuals appear to require higher lower temperature limits (in terms of thermal resistance of summer clothing). It has been observed that elderly individuals tend to prefer warmer temperatures, especially those with higher levels of frailty. Although all frailty levels prefer neutral-warm temperatures, those who are frailer tend to opt for higher temperatures and are more cautious about exposing themselves to cooler environments that might make them ill, likely resulting from a lack of regulation caused by lower physiological function [81].

Different levels of frailty require different thermal needs. Furthermore, the research also observed that the behavioral habits of frailty elderly individuals differ from those of healthy elderly individuals. These differences include a dislike for using air conditioners and fans, a tendency to dress more warmly in the summer, and a preference for staying indoors. These habits may be attributed to their unique thermal needs.

4.3 Subcategories of the elderly

In certain studies on heat sensitivity in older adults, contradictions were found when attempting to classify the elderly population solely based on age [12]. While some studies have shown that individuals aged 85 [31] exhibit greater heat sensitivity than an average age group of 71 [10]or 70 [82], other studies have found the opposite, with people of an average age of 85 displaying lower levels of sensitivity [83]. Certainly, some researchers [34] have recognized this issue, leading to the adoption of clustering methods for age classification in older adults. In these studies, older individuals are categorized into three levels: [60,75), [75,90), and [90,99]. However, this study takes a different approach by redefining the categorization based on frailty levels. It considers the possibility that accelerated aging and increased prevalence of diseases in older individuals may result in varying physiological regulatory abilities at the same chronological age. The findings of this study indeed confirm this notion within the context of physiological regulation.

4.4 Practical applications

The results of this study provide evidence of variations in the thermal demand characteristics of indoor environments amongst elderly individuals with varying levels of frailty. The findings reveal that the distinction in thermal demand characteristics could be attributed to the declining physiological function encountered by frail elderly individuals. Hence, there's a need for attention to be paid when designing housing for the elderly. Specifically, more consideration must be given to the unique requirement of frail elderly individuals, who have a lower body thermoregulatory capacity, and thus, necessitate an accommodating indoor environment that caters to their thermal needs.

5. Conclusions

In an age of increasing aging, it is important to improve the living environment for older people. However, there is a lack of research into the different thermal demand characteristics of the elderly due to aging and reduced physiological capacity. This paper combines non-invasive physiological parameter testing instruments with field research and measurements of environmental parameters in the summer months of Chongqing to find out if there are differences in the thermal demand characteristics of elderly people with different levels of frailty. The main findings from this study have been summarized as followings:

(1) There are significant differences in the characteristics of thermal requirements between elderly people with different frailty levels, especially between those with non-frail and frail levels.

(2) There are different T_n and thermal sensitivity between elderly people with different frailty levels. For example, frail elderly people showed to be more sensitive to the thermal environment and had higher T_n (27.9°C for frail people, 26.9°C for pre-frail people, and 25.8°C for non-frail people).

(3) The frailer the elderly person, the more sensitive they are to changes in temperature and the narrower the range of comfortable temperatures. The comfort temperature intervals of 24.0°C to 30.0°C for non-frailty people, 24.3°C to 29.3°C for pre-frailty people and 25.9°C to 29.3°C for frailty people.

(4) For the survey season, which is summer, there seem to have significantly different physiological regulations between elderly people with different frailty levels. It seemed to be that frail elderly people had low SI and PI, with a high HR. Frail elderly individuals have even lower thermoregulatory abilities.

This study focuses exclusively on the thermal comfort of elderly individuals with varying degrees of frailty, as well as the impact of select physiological parameters on their thermal comfort. Nonetheless, the aging process and physiological degradation in older adults are multifaceted, calling for a more extensive consideration of various physiological parameters. Moreover, the association between physiological parameters and thermal comfort necessitates further theoretical research, which is a direction the research team is pursuing in subsequent investigations on thermal comfort in the elderly. Additionally, it is important to note that this study is a field study, employing portable measuring instruments to monitor physiological parameters. This approach only enables the detection of changes in some physiological indicators, but cannot measure their magnitude with precision (e.g., sweating). Hence, a more meticulous laboratory validation is necessary to more fully reflect the differences in varying degrees of frailty among elderly individuals and to accurately assess thermal comfort in this population.

It is hoped that the study's findings have implications for the design and construction of age-appropriate buildings, which can enhance the comfort and well-being of elderly individuals with different types of frailty. Furthermore, these findings can contribute towards improving the energy efficiency of buildings, without affecting the comfort and health of elderly individuals residing in them. Thus, this study has vital implications for promoting sustainable and effective design standards that are specifically catered to the elderly population.

CRediT authorship contribution statement

Haixia Zhou: Conceptualization, Investigation, Writing-Original Draft, Visualization, Formal analysis.

Wei Yu: Supervision, Writing-Review & Editing, Resources, Project administration, Methodology.

Keyao Zhao: Investigation, Data analysis.

Hanyu Shan: Data collation.

Shan Zhou: Data analysis, Writing - Review & Editing.

Shen Wei: Supervision, Writing - Review & Editing.

Linyuan Ouyang: Data analysis.

All authors read and approved the final manuscript.

Funding

This study was supported by the National Natural Science Foundation of China (Grant Number 52078076).

Data availability

Corresponding authors can provide data used in the study on appropriate request.

Declarations

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

Acknowledgements

The authors would like to thank Yan Zhang and Heqi Wang for assistance in field study and data collection.

References

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

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

[3] R.D. Meade, A.P. Akerman, S.R. Notley, R. McGinn, P. Poirier, P. Gosselin, G.P. Kenny, Physiological factors characterizing heat-vulnerable older adults: A narrative review, Environment International. 144 (2020) 105909. https://doi.org/10.1016/j.envint.2020.105909.

[4] United Nation, World Population Ageing 2019: Highlights (ST/ESA/SER.A/430), Official. (2019).

[5] M. Almeida-Silva, H.T. Wolterbeek, S.M. Almeida, Elderly exposure to indoor air pollutants, Atmospheric Environment. 85 (2014) 54–63. https://doi.org/10.1016/j.atmosenv.2013.11.061.

[6] B. Cao, Y. Zhu, Q. Ouyang, X. Zhou, L. Huang, Field study of human thermal comfort and thermal adaptability during the summer and winter in Beijing, Energy and Buildings. 43 (2011) 1051–1056. https://doi.org/10.1016/j.enbuild.2010.09.025.

[7] L. Ginaldi, M. De Martinis, A. D'Ostilio, L. Marini, M.F. Loreto, D. Quaglino, The immune system in the elderly: III. Innate immunity, Immunologic Research. 20 (1999) 117–126. https://doi.org/10.1007/bf02786468.

[8] A. Mendes, S. Bonassi, L. Aguiar, C. Pereira, P. Neves, S. Silva, D. Mendes, L. Guimarães, R. Moroni, J.P. Teixeira, Indoor air quality and thermal comfort in elderly care centers, Urban Climate. 14 (2015) 486–501. https://doi.org/10.1016/j.uclim.2014.07.005.

[9] D.J. Mancini, S. Allen, Geriatric Physiology, in: R.J. Pignolo, J. Ahn (Eds.), Fractures in the Elderly: A Guide to Practical Management, Springer International Publishing, Cham, 2018: pp. 65–78. https://doi.org/10.1007/978-3-319-72228-3_4.

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

[11] T. Ma, J. Xiong, Z. Lian, A human thermoregulation model for the Chinese elderly,

Journal of Thermal Biology. 70 (2017) 2–14. https://doi.org/10.1016/j.jtherbio.2017.08.002.

[12] Y. Wu, Z. Zhang, H. Liu, B. Li, B. Chen, R. Kosonen, J. Jokisalo, Age differences in thermal comfort and physiological responses in thermal environments with temperature ramp, Building and Environment. 228 (2023) 109887. https://doi.org/10.1016/j.buildenv.2022.109887.

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

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

[15] B. Tejedor, M. Casals, M. Gangolells, M. Macarulla, N. Forcada, Human comfort modelling for elderly people by infrared thermography: Evaluating the thermoregulation system responses in an indoor environment during winter, Building and Environment. 186 (2020) 107354. https://doi.org/10.1016/j.buildenv.2020.107354.

[16] P. Roelofsen, Healthy ageing: differences between elderly and non-elderly in temperature sensation and dissatisfied, Intelligent Buildings International. 9 (2017) 123–136. https://doi.org/10.1080/17508975.2015.1063474.

[17] Paul Roelofsen, Healthy ageing - Design criteria for the indoor environment for vital elderly, Intelligent Buildings International. 6 (2014) 11–25. https://doi.org/10.1080/17508975.2013.830589.

[18] J. Yang, I. Nam, J.-R. Sohn, The influence of seasonal characteristics in elderly thermal comfort in Korea, Energy and Buildings. 128 (2016) 583–591. https://doi.org/10.1016/j.enbuild.2016.07.037.

[19] Y. Jiao, H. Yu, T. Wang, Y. An, Y. Yu, Thermal comfort and adaptation of the elderly in free-running environments in Shanghai, China, Building and Environment. 118 (2017) 259–272. https://doi.org/10.1016/j.buildenv.2017.03.038.

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

[21] Y. Jiao, H. Yu, T. Wang, Y. An, Y. Yu, The relationship between thermal environments and clothing insulation for elderly individuals in Shanghai, China, Journal of Thermal Biology. 70 (2017) 28–36.

https://doi.org/10.1016/j.jtherbio.2017.07.002.

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

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

[24] L. Arakawa Martins, V. Soebarto, T. Williamson, Performance evaluation of personal thermal comfort models for older people based on skin temperature, health perception, behavioural and environmental variables, Journal of Building Engineering. 51 (2022) 104357. https://doi.org/10.1016/j.jobe.2022.104357.

[25] Y. Zhang, J. Zhang, H. Chen, X. Du, Q. Meng, Effects of step changes of temperature and humidity on human responses of people in hot-humid area of China, Building and Environment. 80 (2014) 174–183. https://doi.org/10.1016/j.buildenv.2014.05.023.

[26] K.J. Collins, A.N. Exton-Smith, C. Doré, Urban hypothermia: preferred temperature and thermal perception in old age., Br Med J (Clin Res Ed). 282 (1981) 175–177. https://doi.org/10.1136/bmj.282.6259.175.

[27] N. Hashiguchi, Y. Tochihara, T. Ohnaka, C. Tsuchida, T. Otsuki, Physiological and Subjective Responses in the Elderly When Using Floor Heating and Air Conditioning Systems, Journal of PHYSIOLOGICAL ANTHROPOLOGY and Applied Human Science. 23 (2004) 205–213. https://doi.org/10.2114/jpa.23.205.

[28] K. Natsume, T. Ogawa, J. Sugenoya, N. Ohnishi, K. Imai, Preferred ambient temperature for old and young men in summer and winter, International Journal of Biometeorology. 36 (1992) 1–4. https://doi.org/10.1007/BF01208726.

[29] D.W. DeGroot, W.L. Kenney, Impaired defense of core temperature in aged humans during mild cold stress, American Journal of Physiology-Regulatory, Integrative and Comparative Physiology. 292 (2007) R103–R108. https://doi.org/10.1152/ajpregu.00074.2006.

[30] P. Roelofsen, Healthy ageing and the built environment, Intelligent Buildings International. 6 (2014) 3–10. https://doi.org/10.1080/17508975.2013.775097.

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

[32] M.T. Baquero, N. Forcada, Thermal comfort of older people during summer in the continental Mediterranean climate, Journal of Building Engineering. 54 (2022) 104680. https://doi.org/10.1016/j.jobe.2022.104680.

[33] H. Bennetts, L. Arakawa Martins, J. van Hoof, V. Soebarto, Thermal Personalities of Older People in South Australia: A Personas-Based Approach to Develop Thermal Comfort Guidelines, Int J Environ Res Public Health. 17 (2020) 8402. https://doi.org/10.3390/ijerph17228402.

[34] G. Zheng, C. Wei, X. Yue, K. Li, Application of hierarchical cluster analysis in age segmentation for thermal comfort differentiation of elderly people in summer, Building and Environment. 230 (2023) 109981. https://doi.org/10.1016/j.buildenv.2023.109981.

[35] Y. Tang, H. Yu, Z. Wang, M. Luo, K. Zhang, Y. Jiao, C. Li, Typical winter clothing characteristics and thermal insulation of ensembles for older people in China, Building and Environment. 182 (2020) 107127. https://doi.org/10.1016/j.buildenv.2020.107127.

[36] J.P. Sturmberg, M. Picard, D.C. Aron, J.M. Bennett, J. Bircher, M.J. deHaven, S.M.W. Gijzel, H.H. Heng, J.A. Marcum, C.M. Martin, A. Miles, C.L. Peterson, N. Rohleder, C. Walker, M.G.M. Olde Rikkert, R.J.F. Melis, Health and Disease-Emergent States Resulting From Adaptive Social and Biological Network Interactions, Front Med (Lausanne). 6 (2019) 59. https://doi.org/10.3389/fmed.2019.00059.

[37] M. Cesari, G. Gambassi, G. Abellan van Kan, B. Vellas, The frailty phenotype and the frailty index: different instruments for different purposes, Age and Ageing. 43 (2014) 10–12. https://doi.org/10.1093/ageing/aft160.

[38] D. Marcos-Pérez, M. Sánchez-Flores, S. Proietti, S. Bonassi, S. Costa, J.P. Teixeira, J. Fernández-Tajes, E. Pásaro, B. Laffon, V. Valdiglesias, Association of inflammatory mediators with frailty status in older adults: results from a systematic review and meta-analysis, GeroScience. 42 (2020) 1451–1473. https://doi.org/10.1007/s11357-020-00247-4.

[39] A. Clegg, J. Young, S. Iliffe, M.O. Rikkert, K. Rockwood, Frailty in elderly people, The Lancet. 381 (2013) 752–762. https://doi.org/10.1016/S0140-6736(12)62167-9.

[40] A.A. Romanovsky, Chapter 1 - The thermoregulation system and how it works, in: A.A. Romanovsky (Ed.), Handbook of Clinical Neurology, Elsevier, 2018: pp. 3–43. https://doi.org/10.1016/B978-0-444-63912-7.00001-1.

[41] A.A. Romanovsky, Thermoregulation: some concepts have changed. Functional architecture of the thermoregulatory system, Am J Physiol Regul Integr Comp Physiol. 292 (2007) R37-46. https://doi.org/10.1152/ajpregu.00668.2006.

[42] N.A. Bishop, T. Lu, B.A. Yankner, Neural mechanisms of ageing and cognitive decline, Nature. 464 (2010) 529–535. https://doi.org/10.1038/nature08983.

[43] P.A. Boyle, A.S. Buchman, R.S. Wilson, S.E. Leurgans, D.A. Bennett, Physical frailty is associated with incident mild cognitive impairment in community-based

older persons, Journal of the American Geriatrics Society. 58 (2010) 248–255. https://doi.org/10.1111/j.1532-5415.2009.02671.x.

[44] Ministry of Housing and Urban-Rural Development, GB 50352-2019：Uniform Standards for the Design of Civil Buildings, (2019).

[45] A. Dufour, V. Candas, Ageing and thermal responses during passive heat exposure: sweating and sensory aspects, Eur J Appl Physiol. 100 (2007) 19–26. https://doi.org/10.1007/s00421-007-0396-9.

[46] C.M. Blatteis, Age-Dependent Changes in Temperature Regulation – A Mini Review, GER. 58 (2012) 289–295. https://doi.org/10.1159/000333148.

[47] V. Soebarto, H. Zhang, S. Schiavon, A thermal comfort environmental chamber study of older and younger people, Building and Environment. 155 (2019) 1–14. https://doi.org/10.1016/j.buildenv.2019.03.032.

[48] X. Zhou, Z. Lian, L. Lan, An individualized human thermoregulation model for Chinese adults, Building and Environment. 70 (2013) 257–265. https://doi.org/10.1016/j.buildenv.2013.08.031.

[49] W. Jung, F. Jazizadeh, Vision-based thermal comfort quantification for HVAC control, Building and Environment. 142 (2018) 513–523. https://doi.org/10.1016/j.buildenv.2018.05.018.

[50] S. Liu, S. Schiavon, H.P. Das, M. Jin, C.J. Spanos, Personal thermal comfort models with wearable sensors, Building and Environment. 162 (2019) 106281. https://doi.org/10.1016/j.buildenv.2019.106281.

[51] ANSI/ASHRAE Standard 55-2020：Thermal Environmental Conditions for Human Occupancy, 2020.

[52] 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, Management. 3 (2005) e615.

[53] A.J. Aguilar, M.L. de la Hoz-Torres, M.D. Martínez-Aires, D.P. Ruiz, Thermal Perception in Naturally Ventilated University Buildings in Spain during the Cold Season, Buildings. 12 (2022) 890. https://doi.org/10.3390/buildings12070890.

[54] E. Dent, P. Kowal, E.O. Hoogendijk, Frailty measurement in research and clinical practice: A review, Eur J Intern Med. 31 (2016) 3–10. https://doi.org/10.1016/j.ejim.2016.03.007.

[55] L.P. Fried, C.M. Tangen, J. Walston, A.B. Newman, C. Hirsch, J. Gottdiener, T. Seeman, R. Tracy, W.J. Kop, G. Burke, M.A. McBurnie, Frailty in Older Adults: Evidence for a Phenotype, The Journals of Gerontology: Series A. 56 (2001) M146–M157. https://doi.org/10.1093/gerona/56.3.M146.

[56] P. Ruiz-Grosso, C.L. de Mola, J.M. Vega-Dienstmaier, J.M. Arevalo, K. Chavez, A. Vilela, M. Lazo, J. Huapaya, Validation of the Spanish Center for

Epidemiological Studies Depression and Zung Self-Rating Depression Scales: A Comparative Validation Study, PLOS ONE. 7 (2012) e45413. https://doi.org/10.1371/journal.pone.0045413.

[57] L.S. Radloff, The CES-D Scale: A Self-Report Depression Scale for Research in the General Population, Applied Psychological Measurement. 1 (1977) 385–401. https://doi.org/10.1177/014662167700100306.

[58] A. Ruiz Comellas, G. Pera, J.M. Baena Díez, X. Mundet Tudurí, T. Alzamora Sas, R. Elosua, P. Torán Monserrat, A. Heras, R. Forés Raurell, M. Fusté Gamisans, Validación de una versión reducida en español del cuestionario de actividad física en el tiempo libre de Minnesota (VREM), Revista Española de Salud Pública. 86 (2012) 495–508.

[59] H.L. Taylor, D.R. Jacobs, B. Schucker, J. Knudsen, A.S. Leon, G. Debacker, A questionnaire for the assessment of leisure time physical activities, Journal of Chronic Diseases. 31 (1978) 741–755. https://doi.org/10.1016/0021-9681(78)90058-9.

[60] B.G. Helwig, S. Parimi, C.K. Ganta, R. Cober, R.J. Fels, M.J. Kenney, Aging alters regulation of visceral sympathetic nerve responses to acute hypothermia, Am J Physiol Regul Integr Comp Physiol. 291 (2006) R573-579. https://doi.org/10.1152/ajpregu.00903.2005.

[61] Fanger, O. P., Thermal comfort: analysis and applications in environmental engineering, Thermal Comfort Analysis & Applications in Environmental Engineering. (1972). http://dx.doi.org/.

[62] L.G. Lindberg, P.Å. Öberg, Photoplethysmography - Part 2 Influence of light source wavelength, Medical & Biological Engineering & Computing. 29 (1991) 48–54. https://doi.org/10.1007/BF02446295.

[63] ISO 7726:1998, Ergonomics of the thermal environment — Instruments for measuring physical quantities, Ergonomics. (n.d.).

[64] M. Jowkar, H.B. Rijal, A. Montazami, J. Brusey, A. Temeljotov-Salaj, The influence of acclimatization, age and gender-related differences on thermal perception in university buildings: Case studies in Scotland and England, Building and Environment. 179 (2020) 106933. https://doi.org/10.1016/j.buildenv.2020.106933.

[65] R. de Dear, G.S. Brager, Developing an adaptive model of thermal comfort and preference, (1998). https://escholarship.org/uc/item/4qq2p9c6 (accessed December 27, 2022).

[66] Z. Wang, R. de Dear, M. Luo, B. Lin, Y. He, A. Ghahramani, Y. Zhu, Individual difference in thermal comfort: A literature review, Building and Environment. 138 (2018) 181–193. https://doi.org/10.1016/j.buildenv.2018.04.040.

[67] T. Kainaga, K. Sagisaka, R. Yamada, T. Nakaya, A Case Study of a Nursing Home in Nagano, Japan: Field Survey on Thermal Comfort and Building Energy Simulation for Future Climate Change, Energies. 15 (2022) 936. https://doi.org/10.3390/en15030936.

[68] C.E. de Normalisation, EN 15251: indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, Thermal Environment, Lighting and Acoustics, CEN, Brussels. (2007).

[69] GB/T 50785-2012, Evaluation standard for indoor thermal environment in civil buildings, Standardization Administration of China Beijing, 2012.

[70] S. Zhang, N. Zhu, Gender differences in thermal responses to temperature ramps in moderate environments, Journal of Thermal Biology. 103 (2022) 103158. https://doi.org/10.1016/j.jtherbio.2021.103158.

[71] Building comfort for old age: Designing and managing thermal comfort in low carbon housing for older people, (2014). https://www.housinglin.org.uk/Topics/type/Building-comfort-for-old-age-Designing-and-managing-thermal-comfort-in-low-carbon-housing-for-older-people/ (accessed March 1, 2023).

[72] A. Hansen, P. Bi, D. Pisaniello, M. Nitschke, G. Tucker, J. Newbury, A. Kitson, E. Dal Grande, J. Avery, Y. Zhang, L. Kelsall, Heat-health behaviours of older people in two Australian states, Australas J Ageing. 34 (2015) E19-25. https://doi.org/10.1111/ajag.12134.

[73] R. Bills, V. Soebarto, Understanding the changing thermal comfort requirements and preferences of older Australians, in: 2015. https://www.semanticscholar.org/paper/Understanding-the-changing-thermal-comfort-and-of-Bills-Soebarto/305299cc267889580950008600cf9853e5cc7765 (accessed March 1, 2023).

[74] Investigation and analysis of indoor thermal environment in welfare centers for the aged in Shanghai--《Heating Ventilating & Air Conditioning》2011 年 12 期, (n.d.). https://en.cnki.com.cn/Article_en/CJFDTOTAL-NTKT201112018.htm (accessed March 1, 2023).

[75] Y. Inoue, M. Nakao, T. Araki, H. Murakami, Regional differences in the sweating responses of older and younger men, Journal of Applied Physiology. 71 (1991) 2453–2459. https://doi.org/10.1152/jappl.1991.71.6.2453.

[76] Y. Inoue, T. Kuwahara, T. Araki, Maturation- and Aging-related Changes in Heat Loss Effector Function, Journal of PHYSIOLOGICAL ANTHROPOLOGY and Applied Human Science. 23 (2004) 289–294. https://doi.org/10.2114/jpa.23.289.

[77] C.T. Minson, S.L. Wladkowski, A.F. Cardell, J.A. Pawelczyk, W.L. Kenney, Age alters the cardiovascular response to direct passive heating, Journal of Applied

Physiology. 84 (1998) 1323–1332.

[78] G.F. Mitchell, H. Parise, E.J. Benjamin, M.G. Larson, M.J. Keyes, J.A. Vita, R.S. Vasan, D. Levy, Changes in arterial stiffness and wave reflection with advancing age in healthy men and women: the Framingham Heart Study, Hypertension. 43 (2004) 1239–1245.

[79] Z.J. Schlader, Y. Okada, S.A. Best, Q. Fu, C.G. Crandall, Arterial stiffness during whole-body passive heat stress in healthy older adults, Physiological Reports. 7 (2019) e14094.

[80] A. Arbab-Zadeh, E. Dijk, A. Prasad, Q. Fu, P. Torres, R. Zhang, J.D. Thomas, D. Palmer, B.D. Levine, Effect of aging and physical activity on left ventricular compliance, Circulation. 110 (2004) 1799–1805.

[81] S. Guergova, A. Dufour, Thermal sensitivity in the elderly: A review, Ageing Research Reviews. 10 (2011) 80–92. https://doi.org/10.1016/j.arr.2010.04.009.

[82] C. Bae, H. Lee, C. Chun, Predicting indoor thermal sensation for the elderly in welfare centres in Korea using local skin temperatures, Indoor and Built Environment. 26 (2017) 1155–1167. https://doi.org/10.1177/1420326X16664563.

[83] Y. Jiao, H. Yu, T. Wang, Y. An, Y. Yu, Thermal comfort and adaptation of the elderly in free-running environments in Shanghai, China, Building and Environment. 118 (2017) 259–272. https://doi.org/10.1016/j.buildenv.2017.03.038.