

# Thermal comfort of older adults in hot environments: Experimental and numerical investigation of local cooling devices

Minzhou Chen





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# **Thermal Comfort of Older Adults in Hot Environments: Experimental and Numerical Investigation of Local Cooling Devices**

Minzhou Chen

A doctoral thesis completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at Otakaari 4 (K1) lecture hall 216 of the school on 29, August 2025 at 12:00.

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Older adults, as a vulnerable population, are more susceptible to heat-related mortality during heatwaves than younger individuals. In Finland, recent studies have highlighted this heightened risk. The room (without cooling systems) temperatures will exceed 32°C for about 3000 Kh. In addition, the declining income of the elderly also forces them to consider energy expenditure, thus facing more severe challenges. Some devices already on the market that can provide local cooling may help older people better maintain thermal comfort in hot weather. Compared with air conditioning, these devices are cheaper, more energy-efficient, easier to operate and more portable. However, there is little research on this topic. Thus, this thesis investigates the effectiveness of three types of local cooling devices in enhancing thermal comfort for older adults under various thermal environments. The research comprises four key components: 1) thermal responses of older adults in different thermal conditions; 2) changes in thermal responses after using three local cooling devices; 3) the physiological–psychological correlation of thermal sensation in older adults, and 4) modeling and validation of a novel personal cooling system. The results of the study showed that the neutral temperature of the elderly from northern Europe was 26 °C, their preferred temperature was 26.5 °C and the upper limit of the acceptable temperature was 28 °C. The lowest thermal acceptance rate was observed in environments with high temperature and relative humidity. At 28 °C (60%) and 29 °C (40%), the use of a table fan, evaporative cooling device, or air-cooled jacket could reduce the elderly's thermal sensation to neutral and make more than 80% of people accept the thermal condition. At 33 °C (40%) and 32 °C (50%), the use of an evaporative cooling device or air-cooled jacket reduced thermal sensation significantly, but not to a neutral state. Although thermal acceptance rates increased after using all devices, they were less than 80%, except at 33 °C (40%), when evaporative cooling was used. Furthermore, all three devices performed better under conditions of lower relative humidity. Older adults' skin temperature in the head, limbs, and extremities has the strongest correlation with thermal sensation, and the thermal sensation in the head and torso exerts about 70% influence on overall thermal perception. Skin temperature and device usage had a complex causal relationship, and the cross-lagged effect between the two was the most significant at 5-minute intervals. The proposed novel local cooling system, which combined an evaporative cooling chair and a ventilated jacket can make older adults' thermal sensation reached to 0.5 in room at 33 °C. Meanwhile, it led to a notable 19 % reduction in electric energy consumption while maintaining similar elderly thermal sensation.

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We meet here,  
and we'll meet again somewhere.



Helsinki, 23 June 2025

Minzhou Chen

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# List of Publications

This doctoral thesis is based on the following publications:

- 1.** Chen, M., Farahani, A. V., Kilpeläinen, S., Kosonen, R., Younes, J., Ghaddar, N., ... & Melikov, A. K. (2023). Thermal comfort chamber study of Nordic elderly people with local cooling devices in warm conditions. *Building and Environment*, 235, 110213. <https://doi.org/10.1016/j.buildenv.2023.110213>
- 2.** Chen, M., Younes, J., Farahani, A. V., Kilpeläinen, S., Kosonen, R., Ghaddar, N., ... & Melikov, A. K. (2024). Evaluating thermal response when elderly people using local cooling devices: Correlation among overall and local thermal sensation with skin temperature. *Building and Environment*, 251, 111217. <https://doi.org/10.1016/j.buildenv.2024.111217>
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# Author's Contribution

Article 1: Thermal comfort chamber study of Nordic elderly people with local cooling devices in warm conditions

Minzhou Chen is the main author of this article. The author participated in the design of the experimental protocol and conducted all experimental experiments. The author also performed data collection, data collation and statistical analysis. In addition, the author developed the structure of the article and was responsible for writing the manuscript, responding to reviewer comments and incorporating revision comments. Co-authors Dr. Azin Velashjerdi Farahani and Dr. Simo Kilpeläinen provided extensive assistance during the experimental process. Dr. Azin Velashjerdi Farahani, Dr. Simo Kilpeläinen, Dr. Jaafar Younes, Prof. Nesreen Ghaddar, Prof. Kamel Ghali, Prof. Arsen Krikor Melikov and Prof. Risto Kosonen participated in the design of the experiment, the formation of research ideas, the interpretation of data and the review of the first draft of the article and provided supervision and critical feedback throughout the research process.

Article 2: Evaluating thermal response when elderly people using local cooling devices: Correlation among overall and local thermal sensation with skin temperature

Minzhou Chen is the main author of this article. The author participated in the design of the experimental protocol and conducted all experimental experiments. The author also performed data collection, data collation and statistical analysis. In addition, the author developed the structure of the article and was responsible for writing the manuscript, responding to reviewer comments and incorporating revision comments. Co-authors Dr. Azin Velashjerdi Farahani and Dr. Simo Kilpeläinen provided extensive assistance during the experimental process. Dr. Azin Velashjerdi Farahani, Dr. Simo Kilpeläinen, Dr. Jaafar Younes, Prof. Nesreen Ghaddar, Prof. Arsen Krikor Melikov and Prof. Risto Kosonen participated in the design of the experiment, the formation of research ideas, the interpretation of data and the review of the first draft of the article and provided supervision and critical feedback throughout the research process.

Article 3: Local thermal response differences due to sex and BMI among older adults in warm environments

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Article 4: Enhancing thermal comfort of older adults during extreme weather: Combined personal comfort system and ventilated vest

Minzhou Chen is a co-author of the paper. The author was responsible for conducting the experimental work and providing the experimental data used for model validation. The author also reviewed the manuscript draft and contributed to its revision by offering constructive comments. The principal author, Dr. Jaafar Younes proposed the research idea, developed and calibrated the model, wrote the manuscript, and handled the peer review process, including revisions in response to reviewers' comments.

# List of Abbreviations

AAV	air movement acceptance votes
APV	air movement preference votes
ASHRAE	American society of heating, refrigerating, and air-conditioning engineers
ASV	air movement sensation votes
AVA	arteriovenous anastomose
BMI	body mass index
CEP	corrective-efficiency-to-power
CFD	computational fluid dynamics
CFI	comparative fit index
CP	corrective power
EEG	electroencephalography
Eva	evaporative cooling device
Fan	table fan
FNN	feedforward neural network
HM	higher modes
Jac	air-cooled jacket
LM	lower modes
LSTM	long short-term memory
MS	multiple sclerosis
MST	mean skin temperature
PCA	principal Components Analysis
PCS	personal comfort systems
PMV	predicted mean vote

RH	relative humidity
RMSEA	root mean square error of approximation
RNN	recurrent neural network
SBS	sick building syndrome
TAV	thermal acceptance votes
TLI	Tucker–Lewis index
TPV	thermal preference votes
TS	thermal sensation
TSV	thermal sensation votes

# List of Symbols

a	regression coefficient
b	regression coefficient
c	regression coefficient
d	regression coefficient
$T_a$	air temperature (°C)
$T_{eq}$	equivalent temperature (°C)
$T_{forehead}$	forehead skin temperature (°C)
$T_o$	operative temperature (°C)
$T_{sk}$	skin temperature (°C)
$T_{sk,av}$	mean skin temperature (°C)
$T_{wrist}$	wrist skin temperature (°C)
N	number of test participants
P	probability of statistical significance
R	device use rate (%)
$R^2$	coefficient of determination
$\alpha$	ordinal regression coefficient
$\beta$	ordinal regression coefficient



# 1 Introduction

The dissertation includes this summary and the appended research papers, which all discuss the topic of elderly people's indoor thermal comfort. The introductory section provides the background and the aim of the research. Section 2 outlines the research method, while Section 3 summarizes the results, with a subsequent discussion in Section 4. Finally, Section 5 gives conclusions.

## 1.1 Global Warming and Aging

All facets of human society have undergone significant change since the Industrial Revolution due to the quick development of science and technology. On the plus side, rapid advancements in medical and industrial production have not only greatly increased human lifespan but also improved quality of life. However, there are challenges to these developments as well. For example, the dramatic rise in energy consumption, especially in industrial manufacturing, transportation, and construction, has resulted in significant emission of greenhouse gases, which is one of the primary causes of global warming. Furthermore, as people's lifespans have increased, the world's population is aging more quickly. Therefore, improving energy efficiency, reducing building energy consumption, and ensuring healthy aging of society are essential tasks for the future.

First, biological capacity naturally declines with aging. As a result of this continuous change, the elderly population is currently classified into "frail" and "fit" categories in research (Navarrete-Villanueva et al., 2021). "Frail" refers to older individuals who may be unable to live independently and rely on others for daily activities. These individuals often suffer from chronic conditions such as Alzheimer's disease, hearing loss, and diabetes. Conversely, "fit" refers to older individuals who can do independent daily activities and whose biological capabilities are normal, but potentially declining. Compared to healthy younger individuals, healthy older adults exhibit decreased cardiopulmonary function, slower nervous system reactions, and weakened immunity.

In a hot environment, the human body primarily dissipates heat through two mechanisms: by redistributing blood flow to the skin (vasodilation) to enhance heat transfer from muscles to the skin and then to the environment, and by secreting sweat onto the skin, which evaporates to remove body heat. However, due to

decreased vascular responsiveness, reduced cardiac output, impaired thermoregulatory responses, and increased body fat percentage, the elderly face greater difficulties in dissipating heat (Ebi et al., 2021). These factors make them more vulnerable to high temperatures compared to younger individuals (Tibaldi et al., 2024). Meanwhile, the elderly may require additional time to react to high temperatures because of their decreased ability to detect "heat" and their slow actions (Soebarto et al., 2019). Therefore, the elderly are more likely to suffer heat-related morbidity and mortality in high temperature environments, especially the frail elderly with cardiovascular diseases.

Given that older individuals spend an increasing amount of time indoors, particularly in residential settings, it is essential to ensure their thermal comfort and indoor well-being. However, the trend of global warming has led to more frequent heatwaves and extreme weather events. The polar amplification effect in northern latitudes makes regions like Northern Europe more susceptible to global warming (Bekryaev et al., 2010). In Finland, Jokisalo et al. (Jokisalo et al., 2021) examined summer indoor temperatures in Helsinki apartments. They discovered that during the 2018 heatwave, temperatures in 80% of rooms exceeded 27 °C, with a peak indoor temperature of 32.8 °C in 2019, which exceeded the Ministry of Social Affairs and Health's recommended threshold of 32 °C. Therefore, to provide the elderly with a thermally comfortable environment, it is necessary to understand their thermal comfort requirements and provide corresponding indoor thermal environment adjustment solutions that are appropriate for their needs.

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) defines "thermal comfort" as "that condition of mind that expresses satisfaction with the thermal environment" (ASHRAE, 2021). Currently, the most widely used model for evaluating thermal comfort is Fanger's Predicted Mean Vote (PMV) model, which defines neutral thermal sensation as thermal comfort state. However, the PMV model is based on experiments with average young adults (Ole Fanger & Toftum, 2002). While Fanger and other researchers have suggested that elderly and young individuals do not differ significantly in their thermal preferences, many recent studies have identified substantial differences in thermal comfort between these groups (Z. Wang et al., 2018). As such, the applicability of the PMV model to the elderly remains in question.

To address the challenges posed by global warming and ensure the health and well-being of older adults in high-temperature environments, it is essential to explore the differences in thermal comfort needs between the older and younger adults. Moreover, developing tailored thermal environment control strategies for the elderly is crucial to preserving their health and quality of life.

## 1.2 Indoor thermal environment control methods and individual thermal comfort

According to the scope, methods for regulating indoor thermal environments can be classified into three levels: whole-building regulation, zonal regulation, and individual microclimate regulation (Xie et al., 2020). Typically, centralized air conditioning systems are employed for whole-building regulation, semi-centralized and decentralized systems are used for zonal regulation, while personal comfort systems (PCS) focus on regulating the microclimate around individuals (H. Zhang et al., 2015).

In buildings that utilize centralized or semi-centralized systems, the main goal is to achieve thermal comfort for as many occupants as possible. Nevertheless, these methods are unable to satisfy the requirements of all occupants due to the individual differences in thermal comfort. Individual thermal comfort is defined as the varying thermal perceptions of individuals in the same thermal condition (Z. Wang et al., 2018). Groups with differing attributes, such as age, gender, body type, and living climate zone, exhibit distinct thermal perceptions. Song et al. (Song et al., 2024) found that older adults have reduced thermal sensitivity, a narrower acceptable temperature range, and a preference for warmer environments compared to younger individuals. Zhao et al. (Zhao et al., 2023) reported that female generally feel more comfortable in a warmer condition and feel colder in cool condition, exhibiting greater sensitivity to cold and a stronger preference for warmth. Wang et al. (L. Wang et al., 2023) found a positive correlation between high body fat or muscle mass and a preference for cooler environments, while low body fat or muscle mass correlated with a preference for warmer settings. Additionally, Wang et al. (Z. Wang et al., 2020) highlighted that local climate significantly influences neutral temperature and thermal sensitivity. However, research on different attribute groups remains limited, and no consistent conclusions have been drawn.

The third regulation method, which involves modifying the microclimate around individuals through PCS, has garnered more attention due to the existence of individual thermal comfort. This method has the potential to address the thermal comfort requirements of all occupants. PCS can be classified into three types: radiant, convective, and conductive. The most frequently used cooling PCS are convective types, including ceiling fans, floor fans, and desk fans. These devices are usually portable and operate without pre-treatment systems or air ducts, utilizing indoor air. A particularly personalized and portable PCS is air-cooled clothing. These cooling garments have been extensively studied and applied for individuals engaged in activities with high metabolic rates. However, there is a lack of research on the indoor use of these garments for individuals, including older adults. Furthermore, some convective PCS devices use evaporative cooling technology,

which can lower outlet air temperature, but studies on these systems are also limited (Tejero-González & Esquivias, 2019).

Beyond meeting thermal comfort needs, PCS offer additional benefits for older adults. In fact, besides the physiological challenges that come with aging, some elderly individuals experience "fuel poverty" due to their declining incomes (Healy & Peter Clinch, 2002). Air conditioning is a traditional method for reducing indoor temperatures during hot weather but consumes substantial energy. The operational and maintenance costs of air conditioners can be prohibitively high for many older adults. Moreover, complex air-conditioning control interfaces may be challenging for the elderly to operate, resulting in underutilization (van Hoof et al., 2009, 2010). Therefore, cheap, low-energy, portable and easy-to-operate PCS, as an alternative or supplement to air conditioning, are considered more suitable for the elderly. Additionally, PCS exhibit advantages in responsiveness. Since older individuals may require longer to adjust the environment or themselves to try to maintain thermal comfort. PCS are more responsive than air conditioning systems, particularly the convective and conductive types, as they concentrate on managing the microclimate. This swift response can partially offset the delayed reactions of older adults.

Therefore, to provide older adults with more appropriate indoor thermal regulation solutions and to enhance the theoretical understanding of individual differences in thermal comfort, additional research is required to examine the effectiveness of various cooling PCS applications and the thermal comfort of older adults in a variety of warm environments.

### **1.3 Current study of Personal Comfort Systems (PCS)**

Currently, most studies related to PCS focus on observing physiological and psychological changes before and after using PCS, providing insights into their application scenarios. For instance, in the case of convective cooling PCS, Zhai et al. (Zhai et al., 2013) found that using a floor fan can maintain an 80% thermal acceptability rate in environments of 30 °C with 60% relative humidity. Huang et al. (Huang et al., 2013) demonstrated that with fan speeds of 0 m/s, 1 m/s, and 2 m/s, individuals could maintain a neutral thermal sensation in environments of 28 °C, 30 °C, and 32 °C, respectively. Risetto et al. (Risetto et al., 2021) observed that ceiling fans can sustain occupants' thermal comfort under 28 °C and 31 °C conditions. Meade et al. (Meade et al., 2024) reviewed past studies on fan-related human thermal comfort and concluded that fans are ineffective for personal cooling when ambient temperatures exceed 35 °C. Although these studies provide valuable insights, most of them focus on young adults, with limited research on older adults. Furthermore, much of the data derived from field studies, which may include

confounding factors. Thus, it is necessary to conduct more climate chamber experiments to ensure that the variables are rigorously controlled.

Based on existing PCS studies, evaluation metrics could be primarily divided into objective and subjective indicators. The objective indicator of equivalent temperature ( $T_{eq}$ ) is frequently employed to assess the performance of PCS (Tanabe et al., 1994), since many PCS perform on local body areas, resulting in a non-uniform microclimate. Equivalent temperature is the uniform ambient temperature at which the dry heat loss from a manikin is equivalent to that of a genuine non-uniform environment. Furthermore, subjective indicators describe changes in thermal sensation and comfort before and after using PCS. Zhang et al. (H. Zhang et al., 2015) introduced the concept of "corrective power" (CP), defined as the difference between two ambient temperatures that achieve the same thermal sensation—one without PCS (the reference condition) and one with PCS in use. Additionally, He et al. (He et al., 2017) incorporated PCS power to propose the Corrective Energy & Power (or corrective-efficiency-to-power) index (CEP). However, these subjective indicators are derived from experiments involving young participants and specific PCS types. Given the diverse PCS options and the limited research involving older adults, these metrics are still inadequate.

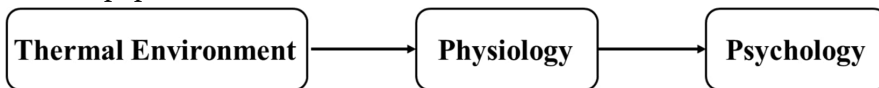
A key feature of PCS is the ability for users to adjust settings flexibly according to their needs. This raises the question: is it necessary to develop automatic control strategies for PCS? Although some studies (Luo et al., 2016; Yun, 2018) suggest that manual control of personal fans may be more beneficial, Boerstra et al. (Boerstra et al., 2015) found that two-thirds of participants preferred automatic control over manual adjustment. Considering the slower response times of older adults, automatic control may be particularly advantageous for this demographic. Current research on PCS control strategies is scarce and primarily focuses on two approaches: (1) predicting the thermal perception of users and (2) directly predicting usage behaviour. The goal of predicting thermal perception is to adjust PCS power based on the psychological state of the user, such as feeling cold/hot or preferring cooler/warmer conditions. However, this approach faces challenges, as thermal perception models typically rely on psychological parameters collected through questionnaires, such as Thermal Sensation Votes (TSV) and Thermal Preference Votes (TPV). Repeated questionnaire responses may cause discomfort and fatigue among participants, and semantic differences in individual cognition may result in inconsistencies in device power adjustments (Rana et al., 2013). Directly predicting individual PCS usage behaviour appears to be a better alternative. However, this method is also challenging, as there is not enough research on the factors that trigger behaviour. Meanwhile, without supplementary information from questionnaires, it is difficult to determine whether the PCS adjustments are appropriate. Therefore, studies (Kim et al., 2018) emphasize the importance of understanding the interaction behaviour between occupants and PCS.

To address the current gaps in PCS research concerning older adults, it is essential to investigate their psychological, physiological, and behavioural responses when using PCS through experimental studies. Evaluating these PCS systems based on such findings will help develop appropriate control strategies for older adults. The results of these studies can provide valuable references for designing next-generation PCS systems.

## 1.4 Current study of thermal comfort models for the elderly

When developing control strategies for centralized, semi-centralized systems, or PCS to ensure human thermal comfort, it is essential to base these strategies on thermal comfort models. For centralized air conditioning, the strategies primarily rely on average thermal comfort models, whereas PCS control strategies are grounded in individual thermal comfort models (this paper considers a range of models aimed at predicting thermal perceptions related to thermal environments, such as thermal sensation, comfort, and preference, as thermal comfort models).

At present, average thermal comfort models are largely based on the concept of the human body as a passive recipient of its thermal environment, as illustrated in Figure 1. These models can be divided into two components: physiological parameter prediction models and thermal perception prediction models based on physiological parameters. They are typically classified into three types: (1) One point model: the PMV model. PMV predicts thermal sensation by calculating the body's heat storage using heat balance equations. Widely applied in centralized and decentralized air-conditioning systems, PMV is suitable for moderate metabolic rate populations in uniform, steady-state environments. However, studies indicate that PMV underestimates thermal sensations of older adults in cold environments and overestimates them in hot environments (Zhou et al., 2023). To address these limitations, researchers have introduced modifications, such as incorporating correction factors (Ole Fanger & Toftum, 2002) or adjusting physiological parameters (Laouadi, 2022) in the heat balance equations to improve predictions for older populations.



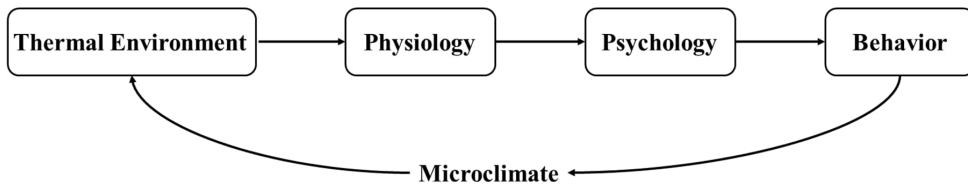
**Figure 1.** The human body passively accepts the thermal environment.

(2) Multi-layer and multi-node human thermoregulatory models based on the one-node model. These models are appropriate for non-uniform transient environments and use numerical simulation to predict the core and skin temperatures of different parts of the human body based on environmental

parameters (Foda & Sirén, 2011; Takahashi et al., 2021). Then, regression analysis is employed to forecast thermal sensation by analysing the predicted skin temperature, core temperature, the deviation of the two from their neutral state, and the rate of change of the two (H. Zhang et al., 2010). There are a limited number of thermoregulatory models designed for the elderly (Hirata et al., 2015), while most present human thermoregulatory models are designed for young individuals. The parameters of the passive and active systems in the thermoregulatory model for young persons are typically adjusted to produce the model for the elderly (Rida et al., 2014). The subsequent thermal comfort model is obtained by correcting the regression coefficient based on thermal response experimental data of the elderly (Younes et al., 2023).

(3) Using biosensors to measure physiological parameters (e.g., skin and core temperatures, heart rate) directly and apply statistical models to predict thermal perceptions (Salehi et al., 2020). There are many such models, but they are usually only modelled for the subjects included in one experiment. The model is usually a simple form such as linear regression, logistic regression, etc (Salehi et al., 2020). Although these models have limited scalability, their strong interpretability aids in understanding physiological and psychological responses. Currently, there are a limited number of climate chamber experiments in older adults, so the number of such models is much smaller than that of younger adults.

Compared to average thermal comfort models, research on individual thermal comfort models is limited. Individual thermal comfort models, particularly in the context of using PCS, emphasize the human body as an active adapter to its environment, illustrated in Figure 2. Early studies incorporated attributes like age, gender, and body type as inputs to develop models tailored to specific groups (Du et al., 2023; Indraganti et al., 2015). However, Feng et al. (Feng et al., 2022) argued that such static attributes are insufficient predictors, as they remain constant over time and fail to capture intra-individual variability. Despite these limitations, previous research provides valuable insights into input features, including environmental parameters (e.g., temperature, humidity) and personal parameters (e.g., skin temperature, heart rate). The selection of optimal input features varies across studies due to differences in modelling methods and data collection techniques. For example, Aryal et al. (Aryal & Becerik-Gerber, 2019) highlighted that combining environmental sensor data with physiological data improves predictive accuracy, while Feng et al. (Feng et al., 2022) found that including behavioural factors yields superior models. Both classical machine learning methods (e.g., linear regression, support vector machines) and modern machine learning techniques (e.g., deep learning) are frequently used to construct these models.



**Figure 2.** The human body actively adapts to the thermal environment.

In general, there are currently few thermoregulatory models or thermal comfort models suitable for the elderly. More experimental data are needed to establish and revise the models, to contribute to the automatic control strategies of centralized, semi-centralized systems and PCS to better ensure the thermal comfort of the elderly.

## 1.5 Objective

In the aforementioned context, the primary aim of this study is to investigate the physiological, psychological, and behavioural thermal responses of Nordic older adults in different warm environments and evaluate the effectiveness of convective cooling PCS. This thesis comprises four publications that collectively form a cohesive work. Based on a series of thermal comfort experiments conducted in climate chambers with older adults, **Publication 1** analyses psychological changes before and after using different PCS and develops a PCS usage model for older adults under varying thermal conditions. **Publication 2** explores changes in physiological changes before and after using different PCS, examining the relationship between local skin temperature, local thermal sensation, and overall thermal sensation. **Publication 3** investigates the influence of gender and body mass index (BMI) on older adults' thermal responses and explores the relationships among skin temperature, thermal sensation, and PCS usage behaviour. **Publication 4** proposes a novel cooling PCS based on findings from **Publication 1-3** to ensure thermal comfort for older adults in warm environments.

The scientific contributions of this research can be divided into three parts:

The first part of the contribution comes from **Publication 1**, **Publication 2**, and **Publication 3**, which explore the thermal response of the elderly in different warm conditions. The effects of air temperature, relative humidity, gender, and BMI of the elderly on skin temperature, thermal sensation, and PCS usage in different warm environments, using data from the climate chamber experiment were analyzed. At the same time, the relationship between the local skin temperature, local thermal sensation, and overall thermal sensation of the elderly was also studied.

The second part of the contribution comes from **Publication 1** and **Publication 3**, which evaluate the effect of different convective cooling PCS through both climate chamber experiments with older adults and thermal manikins. The changes in the elderly's thermal response before and after using different PCS in different thermal environments were analysed. Meanwhile, the equivalent temperature that different PCS at different power levels can create in different thermal environments was calculated.

The third part of the contribution comes from **Publication 2** and **Publication 4**, which design a new type of PCS for the elderly. Through the previously established Bioheat model of the elderly, combined with CFD, a prediction model of the microenvironment around the human body was established when using this new PCS, and the TS model developed previously was used to predict the thermal comfort of the elderly. The model was finally verified by actual experimental data.

This comprehensive research not only deepens the understanding of thermal comfort dynamics for older adults in high-temperature environments but also contributes to the design and optimization of PCS tailored to their specific needs.

## 1.6 Novelty and content of the study

The novelty of this study lies in four key aspects: (1) Focusing on the thermal responses of Nordic older adults in high-temperature environments. (2) Investigating the relationships among physiological, psychological, and behavioral aspects of older adults. (3) Evaluating the effectiveness of various cooling PCS in high-temperature environments. (4) Creating a novel personal climate system to guarantee the thermal comfort of older individuals.

This research primarily involves analyzing changes in physiological parameters, psychological perceptions, and PCS usage behaviors of older adults as thermal environmental conditions vary, based on a series of climate chamber experiments. Additionally, the study employs numerical simulations to design a novel PCS. Table 1 summarizes the entirety of the contents.

**Table 1.** A schematic framework of the study.

Thermal environment	Human thermal response	Climate chamber experiment			Numerical simulation
		Publication 1	Publication 2	Publication 3	Publication 4
Uniform steady state (background environment only, no PCS used)	Physiological		*	*	*
	Psychological	*	*	*	*
	Physiological			*	*

Non-uniform transient state (using and adjusting PCS)	Psychological	*	*
	PCS Usage behavior	*	
Non-uniform steady state (using PCS without further adjustments)	Physiological	*	*
	Psychological	*	*
	PCS Usage behavior	*	

In **Publication 1**, the thermal comfort of older adults was examined in the Nordic region and the contribution of three local cooling devices (table fan, evaporative cooling device, and air-cooled jacket) on thermal and air movement perception under warm conditions was assessed. The first detailed description of how older adults use the evaporative cooling device and air-cooled jacket was provided. This research offers guidance for local indoor environmental regulations and contributes to the future design of intelligent elderly care facilities.

In **Publication 2**, the physiological impacts of three local cooling devices were evaluated under varying warm environments. Body parts were classified based on local thermal sensations and their weights in influencing overall thermal sensation were determined. Additionally, it was confirmed that mean skin temperature remains a reliable metric for assessing overall thermal sensation even after using localized cooling devices and the accuracy of different skin temperature metrics in estimating thermal sensation was compared. These findings are beneficial for designing elderly care facilities or residential environments and for providing recommendations to improve PCS designs.

In **Publication 3**, differences in thermal responses among older adults with gender and BMI were evaluated. It was explored whether the thermal sensations of older adults aligned with their device usage and the relationship between skin temperature and PCS usage behavior was investigated. Furthermore, a deep learning-based model was used to predict individual PCS usage, with its accuracy assessed under different input features. This work provides valuable insights for designing living environments for older adults and establishes a theoretical foundation for developing automatic PCS control systems.

In **Publication 4**, a novel PCS combining an evaporative cooling chair, and a ventilated jacket was proposed. Using the previously developed Bioheat and TS models for older adults, coupled with CFD, the microenvironment around older adults was modelled using this PCS in high-temperature conditions and their thermal sensations were predicted. Meanwhile, the model was validated using prior climate chamber experimental data, and the effectiveness of this new PCS was evaluated.

## 1.7 Research questions

The overall aim of the dissertation is to increase understanding of older adults' thermal response and the effects of different PCS under warm conditions. This topic is approached using four sub-questions which are presented below and summarized in Table 2.

**Table 2.** Research questions and scope of publications.

	<b>Q1:</b> What is the impact of warm environments on the thermal responses of Nordic elderly people?	<b>Q2:</b> How effective are different local cooling PCS in warm environments?	<b>Q3:</b> What is the relationship between skin temperature, thermal sensation and behavior in older adults?	<b>Q4:</b> How to design a new PCS and how effective is it?
Climate chamber experiment for elderly people	Publication 1,2,3	Publication 1,2	Publication 2,3	Publication 1,2
Climate chamber experiment for thermal manikin		Publication 3		Publication 4
Numerical simulation				Publication 4

The first research question focuses on how warm background environment affects older adults' physiology, psychology, and PCS usage behavior.

**Q1: What is the impact of warm environments on the thermal responses of Nordic elderly people?**

**Publication 1, Publication 2,** and **Publication 3** address this question. In **Publication 1**, the impact of background air temperature and relative humidity on the perception of thermal and air movement in the elderly is analyzed and the relationship between air temperature and the power consumed by three PCS quantified. In **Publication 2**, an analysis of the impact of air temperature on the skin temperature and core temperature of the elderly is conducted, resulting in the neutral skin temperature of body parts. In **Publication 3**, the differences in thermal response among various gender and BMI subgroups in elderly participants are analyzed.

The second research question focuses on the performance of different PCS in warm environments.

**Q2: How effective are different local cooling PCS in warm environments?**

**Publication 1, Publication 2, and Publication 3** address this question. In **Publication 1**, the changes in the thermal perception and air movement perception of older adults before and after using three local cooling devices are examined in varying warm conditions. In **Publication 2**, the changes in skin temperature and core temperature of older adults are analyzed before and after using three local cooling devices under different warm conditions. In **Publication 3**, the equivalent temperature of three local cooling devices is calculated under different warm conditions.

The third research question focuses on the correlation between physiology, psychology and behavior when the elderly are exposed to warm environments and use local cooling devices.

**Q3: How is skin temperature related to thermal sensation and behavior in older adults?**

**Publication 2 and Publication 3** address this question. In **Publication 2**, the correlation between local thermal sensation and local skin temperature, the correlation between local thermal sensation and overall thermal sensation, and the correlation between mean skin temperature and overall thermal sensation are analyzed before and after using local cooling devices. In **Publication 3**, the correlation between skin temperature and behavior during the use of PCS is analyzed. Furthermore, based on skin temperature, deep learning was used to predict the PCS usage behavior of older adults.

The fourth research question focuses on creating a new PCS to meet the thermal comfort needs of the elderly in warm environments.

**Q4: How to design a new PCS and how effective is it?**

**Publication 1, Publication 2, and Publication 4** address this question. The results of the local thermal sensation weighting analysis in **Publication 2** provide a theoretical basis for the creation of a new PCS. In **Publication 4** CFD, combined with the Bioheat model (elderly thermal physiological model) and the TS model (elderly thermal sensation prediction model), is used to design a new PCS that combines an evaporative cooling chair and an air-cooled jacket. The effect of the new PCS is verified by the results of the climate chamber thermal manikin experiments in **Publication 4** and the results of the climate chamber elderly people experiments in **Publication 1**.

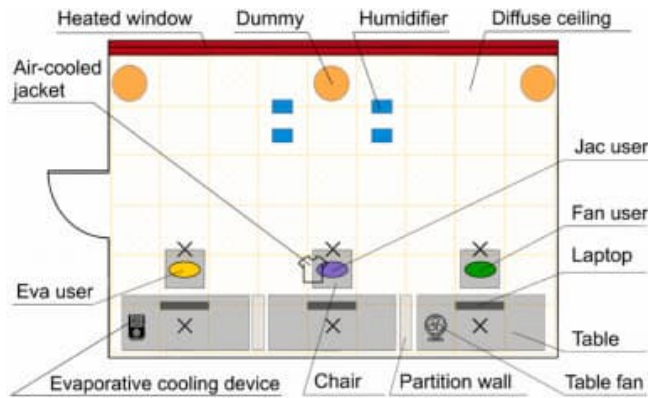
## 2 Methods

This section begins with the procedures of climate chamber experiments involving elderly people (**Publication 1,2,3**) and thermal manikin (**Publication 3,4**). Then, the thermoregulatory model (Bioheat model) and thermal sensation model (TS model) of elderly people are introduced (**Publication 4**). Finally, the CFD model which evaluates the microclimate around the human body created by the novelty PCS is described in detail (**Publication 4**).

### 2.1 Climate chamber in Aalto University

#### 2.1.1 Climate chamber layout

This experiment was conducted in a climate chamber. The climate chamber was 5.5 m long, 3.8 m wide, and 3.2 m high and located in a laboratory hall. It comprised of a diffuse-ceiling ventilation system, heated simulation windows, and humidifiers (Figure 3). Ventilation air was supplied through 14-mm diameter nozzles drilled in the ceiling panels, which covered the entire ceiling. The perforation rate of the panels was  $0.50 \pm 0.02\%$ . The walls comprised seven heated windows (0.6 m  $\times$  1.79 m each). The temperature of the heated windows was controlled using a water system. Four automatically controlled humidifiers, providing steam at a temperature equal to indoor air temperature ( $T_a$ ), were in the middle of the side with the heated windows. Three sets of a table with a computer and a chair were arranged on the side opposite to the windows and were separated by partition walls. Three different local cooling devices were assigned to the three tables, including a table fan (Fan), an evaporative cooling device (Eva), and an air-cooled jacket (Jac).



**Figure 3.** Climate chamber test layout. (where, × = the location of the sensor that measures air temperature and relative humidity).

### 2.1.2 Test conditions

According to the Finnish national building codes and regulations, the maximum allowable indoor air temperature during the design phase is 27 °C outside the heating season. For occupied apartments, the indoor air temperature should not exceed 32 °C – or 30 °C for vulnerable individuals – to ensure the health and well-being of occupants in all living spaces. However, previous research (Farahani et al., 2021) estimated that in Finland in 2050, rooms without cooling systems will experience more hours above 32 °C (the amount of degree hours is about 3000 Kh), whereas rooms with ventilation systems will experience more hours above 27 °C (the amount of degree hours a is about 14,000 Kh). Consequently, five experimental conditions with different air temperature ( $T_a$ ) and relative humidity (RH) were chosen to represent Finland's typical summertime and heat wave periods, including  $T_a = 26$  °C, RH = 40%; 28 °C, 60%; 29 °C, 40%; 32 °C, 50%; and 33 °C, 40%. When analyzing the effects of environmental parameters on thermal response of older adults, RH is denoted by (T) and (H) for typical RH (40%) and higher RH (50% or 60%), respectively. Meanwhile, based on the PMV model, these five conditions can also be divided into three types: neutral (26 °C, 40% relative humidity (RH)), slightly warm (29 °C, 40% RH; 28 °C, 60% RH), and warm (33 °C, 40% RH; 32 °C, 50% RH).

In the climate chamber,  $T_a$  was controlled by balancing the heat gains and the cooling load. Supply air temperature was 17 °C, approximately 15 °C lower than the room air temperature in the warmest conditions. Overall heat gain during the experiment included the heat gains from human subjects, lighting systems, computers, and heated simulated windows. Three heated dummies (cylindrical heat sources with 0.4-m diameter and 1.1-m height) were also used to balance the heat gains and were placed in front of the heated window side. Each test involved three

human subjects, and in case participants were missing from a test, dummies were used to replace their heat gain and maintain a constant  $T_a$ . Input parameters were calculated based on the heat balance required to reach the target  $T_a$ . Details of the operating settings for the five experimental conditions are summarized in Table 3. The Standard EN15251 Category B for low-polluting buildings has set the ventilation airflow rate at 2 L/(s, m<sup>2</sup>), which was the basis for this study. Total airflow rate was constant at 42 L/s.

**Table 3.** Different operation settings in five indoor climate conditions.

Case	Relative Humidity (%)	Air flow rate (L/s)	Supply air temperature (°C)	Exhaust air temperature (°C)	Subject (W)	Lighting (W)	Computer (W)	Dummies (W)	Window panels (W)
26 °C (T)	40%	42	17	26	166	85	165	40	0
29 °C (T)	40%	42	17	29	166	85	165	0	190
28 °C (H)	60%	42	17	28	166	85	165	0	190
33 °C (T)	40%	42	17	33	166	85	165	200	190
32 °C (H)	50%	42	17	32	166	85	165	200	190

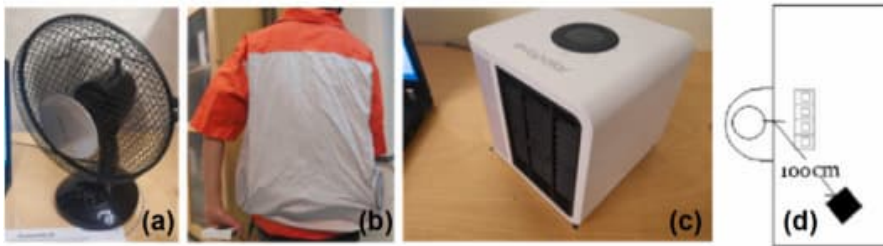
The  $T_a$  and RH in the climate chamber were measured with six TinyTag 2 plus data loggers ( $T_a$  accuracy:  $\pm 0.5$  °C, RH accuracy:  $\pm 3$  %). The measured environmental data for the chamber conditions are listed in Table 1. The operative temperature ( $T_o$ ) and air velocity were measured with Dantec ComfortSense probes ( $T_o$  accuracy:  $\pm 0.2$  °C, air velocity accuracy:  $\pm 0.02$  m/s) in 26 °C, 40 % RH, 29 °C, 40 % RH, and 32 °C, 50 % RH. The difference between  $T_o$  and  $T_a$  was less than 0.5 °C. Air velocity in the occupied zone was less than 0.05 m/s. The measured environmental data for the chamber conditions are listed in Table 4.

**Table 4.** Actual measurements of the environmental parameters.

Case ( $T_a$ /RH)	Test conditions (mean $\pm$ SD)		
	$T_a$	RH	$T_o$
Neutral 26 °C/40%(T)	25.7 $\pm$ 0.5 °C	42 $\pm$ 2%	25.8 $\pm$ 0.3 °C
Slightly warm 28 °C/60%(H)	28.3 $\pm$ 0.5 °C	62 $\pm$ 5%	–
	29 °C/40%(T)	29.0 $\pm$ 0.5 °C	29.1 $\pm$ 0.3 °C
Warm 32 °C/50%(H)	31.7 $\pm$ 0.6 °C	48 $\pm$ 3%	31.8 $\pm$ 0.3 °C

### 2.1.3 Three local cooling devices

This study used the following local cooling devices: (a) Fan: table fan, (b) Jac: air-cooled jacket, and (c) Eva: evaporative cooling device (Figure 4(a)(b)(c)). The table fan was 230 mm in diameter with three blades. It had two speeds and an electric power range of 0–25 W. The air-cooled jacket, designed to be worn over clothing, consisted of a spacer vest liner with an impermeable outer layer, two 97-mm wide fans placed symmetrically on the lower back, an internal pocket for a rechargeable battery, and weighed 0.7 kg. The bottom of the jacket was sealed off with a ring of elastic material, allowing air to escape only through the top. When in use, the fans were activated simultaneously to supply ambient air to the torso. It had four speeds and an electric power range of 0–20 W. The evaporative cooling device was 180 mm × 180 mm × 182 mm. It had a medium that was humidified via capillary action using water from a small side tank (1000 mL) and a small fan with 10 speeds and an electric power range of 0–10 W.



**Figure 4.** Local cooling devices and their positions: (a) table fan, (b) air-cooled jacket, and (c) evaporative cooling device. (d) The placement of table fan and evaporative cooling device on the table.

The table fan and evaporative cooling device were fixed to Table 1 m away from the subject (Figure 4(d)). The device angle was adjusted such that airflow was directed toward the torso rather than the head to minimize unwanted symptoms, such as dry eyes and headaches. The jacket size (small, medium, or large) was selected based on the participant's body size.

## 2.2 Thermal manikin experiments in Aalto University climate chamber

Thermal manikin experiments were conducted in the climate chamber described in Section 2.1 with three main objectives: 1) to measure the air velocity around the human body when using selected local cooling devices; 2) to determine the exposed

body parts when using three local cooling devices; and 3) to quantify the heat dissipation capacity of these local cooling devices.

### 2.2.1 Thermal manikin information

The experiment used a thermal manikin (175 cm tall male) from PT TEKNIK with 27 separate skin segments: top, left side, and right side of head; left and right upper chest; left and right lower chest; front and back of pelvis; left and right upper back; left and right lower back; left and right upper arms; left and right forearms; left and right hands; left and right front thighs; left and right back thighs; left and right front lower legs; and left and right feet. There are three control modes for the manikin: constant surface temperature mode, constant heat flux mode, and comfort mode. Comfort mode was selected for this experiment, which means the surface temperature of the segments of the manikin was controlled to be the same as the skin temperature of a person in a state of thermal neutrality.

The thermal manikin simulated the participant sitting in a chair, wearing a short-sleeved T-shirt, trousers, socks, and shoes (0.5 clo in total) (Figure 5). Because the manikin lacks a sweating module, RH has no effect on it; therefore, the experiment was only conducted under three conditions, all at 40 % RH: neutral (26 °C), slightly warm (29 °C), and warm (32 °C).

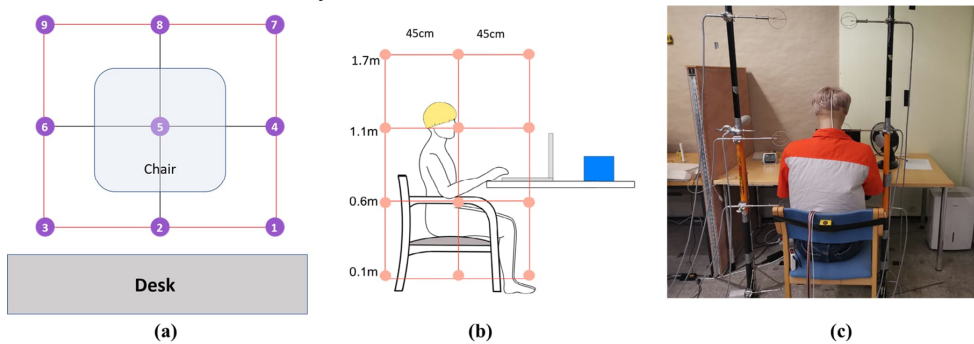


**Figure 5.** Thermal manikin test with (a) the table fan and (b) the air-cooled jacket. (the evaporative cooling device positioned identically to the table fan.)

### 2.2.2 Test procedure and data collection

Nine locations (including the centre point) were chosen around the thermal manikin (the centre and locations at a distance of 45cm from it) to measure the air velocity generated by the local cooling device. The air velocity was measured at four heights (0.1m, 0.6m, 1.1m, and 1.7m) at all nine measurement points, as shown in Figure 6. The sensors for measuring air velocity include 1 Dantec ComfortSense (scale: 0-1 m/s, accuracy:  $\pm 0.02$  m/s) and 7 SensorElectronic SensoAnemo (scale:

0.05–5 m/s, accuracy:  $\pm 0.02$  m/s) omnidirectional probes. These 8 sensors were fixed on two poles, with Dantec ComfortSens located at a height of 0.1m. The air velocity at a total of 36 points was recorded at a frequency of 0.5 seconds for three minutes. The final air velocity of the point was the average value of the three-minute measurement. The air velocity information of three local cooling devices is presented here as supplementary information to Section 2.1.3, as the human body's specific impact of air velocity is not addressed in the subsequent research content. It is worth noting that the air velocity values for different devices in Table 5 are not the same. For table fan and evaporative cooling device, the velocity represents the average velocity near head and chest; for air-cooled jacket, the velocity corresponds to the fan outlet air velocity.



**Figure 6.** Air velocity measurement at (a) nine different locations and (b) four different heights with (c) eight sensors.

**Table 5.** Specifications of the three local cooling devices.

Local cooling device	Power (W)	Speed (mode)	Velocity (m/s)
Table fan	0–25	1	0.25
		2	0.31
Evaporative cooling device	0–10	1	0.10
		2	0.12
		3	0.14
		4	0.16
		5	0.18
		6	0.21
		7	0.23
		8	0.25
		9	0.27
		10	0.29
Air-cooled jacket	0–20	1	1.40

2	2.20
3	2.60
4	3.30

---

To determine the body parts that were affected by local cooling devices when using different devices with different speeds, the surface temperature and electricity consumption of 27 segments were collected every 10 s by the supporting software until all parameters reached a steady state. Under steady-state conditions, the amount of heat supplied to the manikin heating elements was equivalent to the amount of heat lost from the surface. Thus, the heat loss of each segment could be derived from its electricity consumption. The greater the electricity consumption, the greater the heat dissipation of each part was. By comparing the electricity consumption of each part when no local cooling device was used, the parts exposed to local cooling could be identified.

To objectively evaluate the heat dissipation capabilities of the three local cooling devices, the equivalent temperature ( $T_{eq}$ ) was adopted. The  $T_{eq}$ —defined as the uniform ambient temperature at which the dry heat loss of the manikin matches that in an actual non-uniform environment—is commonly used to assess non-uniform thermal conditions. On the thermal manikin test, although each of the 27 segments of the manikin could provide the local  $T_{eq}$ , the primary focus was on the overall changes. Consequently, only the overall  $T_{eq}$  values were considered. The calculation formula is as follows:

$$= \frac{Q}{h_{cal}} \quad (1)$$

where  $T_{sk}$  is the surface temperature of the thermal manikin,  $Q$  is the electrical power of the thermal manikin, and  $h_{cal}$  is the calibration coefficient.

## 2.3 Elderly people experiments in Aalto University climate chamber

Elderly people experiments were conducted in the climate chamber described in Section 2.1 with three main objectives: 1) to explore the thermal response of the elderly in different thermal environments; 2) to find the changes in thermal response of the elderly before and after the use of local cooling devices; 3) to explore the relationship between skin temperature, thermal sensation and behavior of the elderly.

### 2.3.1 Elderly participants information

This study was approved and supported by the Aalto University Research Ethics Committee (D/793/April 03, 2021, approved on Sep 23rd, 2021). Participants were

required to be free of multiple sclerosis (MS), Parkinson's, kidney disease, or previous paralysis or heart attack. Furthermore, participants with age-related memory impairments were excluded because it was difficult for them to comprehend the study.

26 healthy Finnish older individuals (aged > 65 years) were recruited. One objective of the experiments was to explore the differences in thermal responses among older adults of different gender and body builds. Body build was represented by BMI. Thus, the participants were categorized into female/male groups and normal ( $BMI \leq 25$ )/overweight groups ( $BMI > 25$ ). Table 6 provides detailed information about the participants.

**Table 6.** Anthropometric data of the older adult participants.

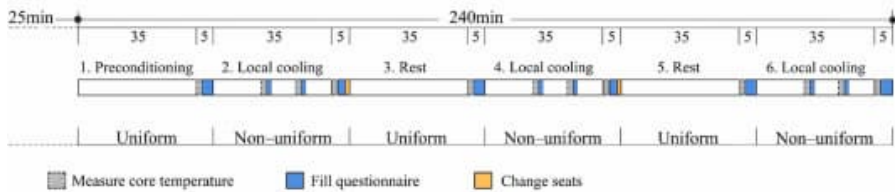
Anthropometric unit (mean $\pm$ SD)	Female (N=19)	Male (N=7)	Normal (N=12)	Overweight (N=14)
Age (years)	70.8 $\pm$ 6.0	70.9 $\pm$ 5.5	70.7 $\pm$ 5.3	70.9 $\pm$ 6.3
Height (cm)	161.8 $\pm$ 4.6	177.7 $\pm$ 4.0	166.5 $\pm$ 8.8	165.7 $\pm$ 8.4
Weight (kg)	67.6 $\pm$ 9.6	78.5 $\pm$ 8.7	63.0 $\pm$ 9.1	77.0 $\pm$ 6.6
Waist circumference (cm)	94.0 $\pm$ 11.3	95.3 $\pm$ 7.3	87.0 $\pm$ 8.8	100.6 $\pm$ 6.6
Neck circumference (cm)	35.6 $\pm$ 2.3	39.7 $\pm$ 1.5	35.5 $\pm$ 3.1	37.6 $\pm$ 2.2
BMI (kg/m <sup>2</sup> )	25.9 $\pm$ 3.9	24.8 $\pm$ 2.2	22.6 $\pm$ 1.9	28.1 $\pm$ 2.4

The participants underwent a training session before the test. During this session, precautions and experimental procedures were explained to the participants. The experimental precautions included: 1) Evasion from alcohol or coffee consumption within the 24 h before the experiment; 2) Wearing short-sleeved T-shirts, trousers, socks, and shoes (0.5 clo) for all the tests; the clothing should not be loose enough to hinder wearing the air-cooled jacket; and 3) Participants could drink but not eat during the test periods. In the climate chamber, the subjects were provided with a bottle of water placed in advance on the desk. 4) Participants were not allowed to communicate with each other about the experiment during the test. During the training session, the researcher explained in detail the procedures of completing the questionnaires used during the experiment and use of the three local cooling devices. Each participant participated in the experiment once a week for five weeks. The number of participants in each test condition varied because not every participant could participate in the experiment on time. Because not every participant was able to participate each time, the number of test participants (N) in each condition varied. The experiment included

five conditions: neutral (26 °C, 40 % RH, N = 26), slightly warm (29 °C, 40 % RH, N = 24; 28 °C, 60 % RH, N = 26), and warm (33 °C, 40 % RH, N = 20; 32 °C, 50 % RH, N = 23). The test included five conditions: neutral (26 °C/40%); slightly warm (28 °C/60%, 29 °C/40%); and warm (32 °C/50%, 33 °C/40%).

### 2.3.2 Test procedure and data collection

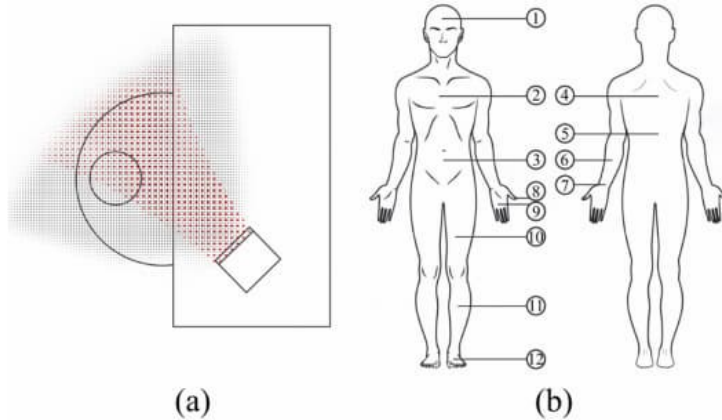
The experimental process is illustrated in Figure 7. Each test lasted 4 h and consisted of six phases, each lasting 40 min. Participants entered the climate chamber 25 min earlier for pre-test preparations, such as clothing changes (clothing insulation was 0.5 clo in all tests) and sensor attachment. During the preconditioning phase, the participants were instructed to remain sedentary to adapt to the test environment. During this period, participants were permitted to use computers or read. During the subsequent local cooling phase, the participants were permitted to rotate the knobs to modify the speed mode of the given local cooling device (Table 5) based on their individual needs; however, they were not permitted to alter the position or angle of the table fan or the evaporative cooling device. The subsequent four phases repeated the first two phases, in which the participants sat for 40 min before using the cooling device for another 40 min. At the end of each local cooling phase, the three participants changed their positions to ensure that they each utilized all three devices. During the final 5 min of each phase, each participant completed a questionnaire (long type) and underwent tympanic temperature measurement. Two additional questionnaires (short type) and tympanic temperature measurements were done at 15 and 25 min in each local cooling phase. Phases 1, 3, and 5 correspond to a uniform environment, whereas phases 2, 4, and 6 correspond to a non-uniform environment after the use of local cooling devices.



**Figure 7.** Schedule of elderly people experiment.

During the experiment, participants' skin temperature was continuously measured using iButton sensors (DS1923, accuracy of  $\pm 0.5$  °C in the test range of  $-10$ – $65$  °C). The measured body parts were the forehead, chest, pelvis, upper back, lower back, forearm, wrist, palm, thumb, thigh, calf, and foot. Owing to the

placement of the table fan and evaporative cooling device, the airflow acted more on the left side of the body (Figure 8(a)) and hence, the measurement points of the limbs and extremities were all on the left side (Figure 8(b)). The tympanic temperature was measured using an ear temperature gun (Braun IRT6520, accuracy of  $\pm 0.2$  °C in the test range of 34–42.2 °C) and was interpreted as the core temperature (Brinnel & Cabanac, 1989).



**Figure 8.** (a) Air distribution of the table fan and evaporative cooling device; (b) skin temperature measurement points: 1. forehead; 2. chest; 3. pelvis; 4. upper back; 5. lower back; 6. forearm; 7. wrist; 8. thumb; 9. palm; 10. thigh; 11. calf; 12. foot.

In this experiment two types of questionnaires were utilized to record the psychological parameters of the participants: long and short, as shown in Table 7. The long questionnaire elicited responses regarding participants' overall thermal perception (thermal sensation, thermal comfort, thermal preference, and thermal acceptance) and overall air movement perception (air movement sensation, air movement preference, air movement acceptance, and air movement disturbance). Meanwhile, this questionnaire included questions about local thermal sensations (forehead, chest, pelvis, upper back, lower back, forearm, palm, thigh, calf, and foot). Additionally, some symptoms chosen from common sick building syndrome (SBS) were also listed in the long questionnaire. Due to time limitations and to avoid fatiguing the participants, questions about local air movement sensation were not asked, and the focus was on local thermal sensation. The short questionnaire only involved overall thermal sensation, thermal comfort, thermal acceptance, air movement sensation, and air movement disturbance.

**Table 7.** Thermal perception and air movement perception questionnaires.

Questions	Scale to the query	Type
Rate your current thermal sensation of whole body		Long, Short

Rate your current thermal sensation of forehead		Long	
Rate your current thermal sensation of chest		Long	
Rate your current thermal sensation of pelvis		Long	
Rate your current thermal sensation of upper back		Long	
Rate your current thermal sensation of lower back	-3 (cold), -2 (cool), -1 (slightly cool), 0 (neutral), 1 (slightly warm), 2 (warm), 3 (hot)	Long	
Rate your current thermal sensation of forearm		Long	
Rate your current thermal sensation of palm		Long	
Rate your current thermal sensation of thigh		Long	
Rate your current thermal sensation of calf		Long	
Rate your current thermal sensation of foot		Long	
Rate your current whole body thermal comfort		-3 (very cold uncomfortable) to 3 (very hot uncomfortable)	Long, Short
Rate your current whole body thermal acceptability		-3 (clearly unacceptable) to 3 (clearly acceptable)	Long, Short
Rate your current whole body thermal preference		-3 (greatly cooler), -2(cooler), -1(slightly cooler), 0 (no change), 1(slightly warmer), 2(warmer), 3 (greatly warmer)	Long
Rate your current whole body air movement sensation	0 (no air movement), 1 (slight air movement), 2 (moderate air movement), 3 (strong air movement)	Long, Short	
Rate your current whole body air movement acceptability	-3 (clearly unacceptable) to 3 (clearly acceptable)	Long	
Rate your current whole body air movement preference	-3 (add a lot of airflow), -2(add airflow), -1(add a little airflow), 0 (no change), 1(reduce a little airflow), 2(reduce airflow), 3 (reduce a lot of airflow)	Long	
Rate how much the current airflow disturbs you	0 (not disturb), 1 (disturb), 2 (strong disturb)	Short	
Do you have any of the following symptoms?	headache, eye irritation, nose irritation, throat irritation, dry skin	Long	

## 2.4 Statistical analysis

Statistical analyses were performed using SPSS 20.0, GraphPad Prism 9, and MATLAB. Results were considered statistically significant at  $p < 0.05$ . “\*” and “\*\*\*” indicates a significant difference of  $p < 0.05$  and a highly significant difference of  $p < 0.01$ , respectively. Analytical results were visualized using R, GraphPad Prism 9, and Origin Pro.

When analyzing (1) the correlation between environmental parameters and skin temperature; (2) the correlation between environmental parameters and psychological parameters; (3) the correlation between (local/mean) skin temperature and (local/overall) thermal sensation; (4) the correlation between the change in local skin temperature and the change in local thermal sensation, Pearson correlation analysis was applied, and then, for (1) and (2), linear regression was used to build relationships between parameters.

When analyzing the effect of air temperature on cooling device usage rate, logistic regression, as a common method for analyzing binary response variables, was used to describe the relationship between air temperature and device usage rate. Ordinal regression analysis is the extension of binary logistic regression, which could be used when the categorical variable has more than two levels with ordinal nature. Since each device has several ordinal speeds, this study used ordinal regression analysis to further explore the usage rate under different power levels. Nagelkerke's pseudo  $R^2$  was applied to evaluate the goodness-of-fit of the model.

The aim was also to investigate the differences in thermal response among older adults of different gender and BMIs in warm environments. The thermal responses included changes in physiology, psychology, and device power usage with rising temperature. To examine the differences between the groups and how these differences varied with temperature, we used the following formula:

$$Y = a + bX + cZ + d(XZ) \quad (2)$$

where  $Y$  represents the thermal response,  $X$  denotes gender or BMI, coded as 0/1 (0 = female, 1 = male; 0 = normal BMI, 1 = overweight, and thus in the group analysis of gender, females served as the baseline, and in the group analysis of BMI, the normal group served as the baseline), and  $a$ ,  $b$ ,  $c$ , and  $d$  are regression coefficients.

The slope coefficient  $d$ , influenced by gender or BMI, reflects variations in thermal response between different groups as the temperature changes, indicating differences in sensitivity. Here, sensitivity refers to the variation in thermal sensation, skin temperature, or device usage power with a  $1^\circ\text{C}$ - increase in  $T_a$ . A smaller  $d$  value indicates smaller differences in sensitivity between the groups. The intercept coefficient  $b$ , which is influenced by gender or BMI, reflects fixed

differences in thermal responses between the groups, which persist even when  $d = 0$  (group sensitivities are identical). The statistical significance of the coefficients was evaluated using *t*-tests.

When analyzing the effect of local cooling devices on older adults' physiological and psychological parameters, the paired *t*-test was applied to compare the votes and skin temperature before and after using local cooling devices. Furthermore, under each condition, participants voted three times in each local cooling phase. Therefore, physiological and psychological parameters at different time points were compared using a repeated-measures ANOVA (Greenhouse–Geisser adjustment) to observe the trend of these parameters. Shapiro-Wilk test was used to determine normal distribution.

A weighting factor method was used to specify the relationship between local thermal sensation and overall thermal sensation in uniform steady state (without local cooling devices). To avoid multicollinearity between local thermal sensations of each body part, the Principal Components Analysis (PCA) was used to extract some uncorrelated eigenvectors from the related matrix of local thermal sensations first, and then used multiple regression to build the model between overall thermal sensation and these eigenvectors (Jin et al., 2012).

PCA can extract fewer new variables from multiple initial variables while retaining as much information of the initial variables as possible. In addition, there is no correlation between these new variables, which effectively solves the multicollinearity problem. However, the main purpose of PCA is data reduction (i.e., translating a variable space into an optimal factor space), not detecting latent constructs or factors. Thus, factor analysis (Neziri et al., 2011; Yoshida et al., 2015), a correlation-focused approach seeking to reproduce the intercorrelations among variables based on PCA, was used to further analyze the local thermal sensation data after using local cooling devices, making the results more interpretable.

The data used in the above analysis are all from the end of each phase, that is, the steady state.

To analyze more complex causal relationships, path analysis (Kim et al., 2018; Y. Peng et al., 2021; Streiner, 2005) was employed. Compared to standard regression and black-box models, path analysis allows for the simultaneous examination of complex interactions and causal relationships among multiple variables. In this study, path analysis involved basic linear forms without incorporating non-linear terms, which enhanced the model's interpretability. The cross-lagged panel model, a type of path analysis, is particularly appropriate for longitudinal data as it can analyze the mutual influence between variables at multiple time points, thereby providing a comprehensive view of the interactions among variables. A cross-lagged panel model was employed to explore the relationship between skin temperature and device usage. The analyses were conducted using Mplus version 8.3.

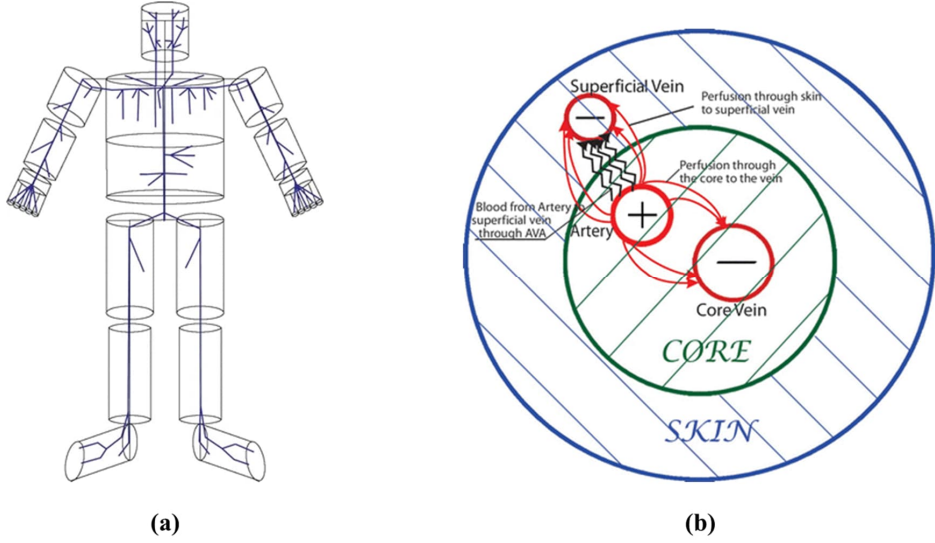
Long short-term memory (LSTM) networks were employed to predict the participants' dynamic usage of the devices. In a common feedforward neural network (FNN), information flows in only one direction, and the nodes between layers are not interconnected, making an FNN more suitable for analyzing cross-sectional data samples. In contrast, recurrent neural network (RNN) feature neurons that self-connect along a time sequence, allowing information to flow in both directions due to loops incorporated into the architecture, thus making RNNs better suited for time-series data. Although RNNs can effectively handle non-linear time series, their susceptibility to vanishing gradients can lead to neglecting early-stage information in prediction or classification tasks. To address this issue, Hochreiter et al. proposed LSTM networks that utilize memory cells and gating mechanisms to capture long-term dependencies. Thus, the LSTM (Y. Wang et al., 2017) was used to predict participants' device usage. Python 3.9 was employed as the development language and the Spyder integrated development environment. The LSTM model was implemented employing program development using PyTorch.

## **2.5 Numerical simulation for elderly people when using novel PCS**

In this study, 1) an elderly bioheat model and a thermal sensation (TS) model to predict the physiological and psychological responses of the elderly under different systems and environmental conditions; 2) a ventilated jacket microclimate model for predicting heat and mass exchanges with the human trunk; and 3) a CFD model to predict the airflow and temperature field when the cooling chair and ventilated jacket are employed.

### **2.5.1 Thermoregulatory model of elderly people: Bioheat model**

The elderly bioheat model of Rida et al. (Rida et al., 2014) is adopted to predict physiological responses of elderly individuals under different thermal conditions, with and without the proposed PCS. This model is a transient, multi-segment, multi-node, clothed bioheat model that considers the physiological changes that occur with aging (Figure 9(a)). Each segment in the model consists of four nodes (Figure 9(b)) where the energy equation is solved: the core node, skin node, artery node, and vein node. For a given metabolic rate, clothing insulation, and environmental conditions around the occupant, the model can predict the physiological response, mainly the segmental skin and core temperatures.



**Figure 9.** (a) The segments of the human body used in the bioheat model; (b) Different nodes of the peripheral body segments including artery, core vein, and superficial skin vein nodes.

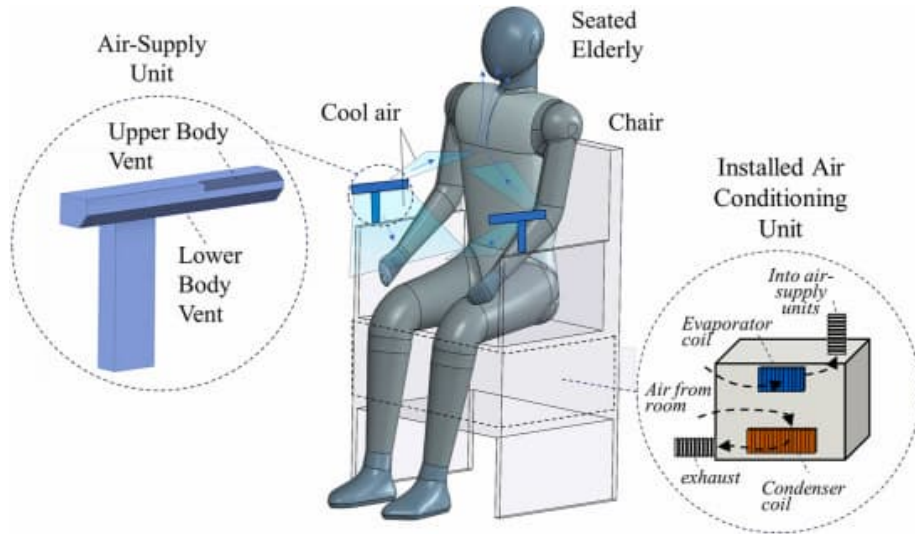
### 2.5.2 Thermal sensation model of elderly people: TS model

The prediction of elderly TS is accomplished by utilizing the elderly sensation model developed by Younes et al. (Younes et al., 2023). The model accommodates age-related variations in thermal sensitivity to environmental stimuli. When compared to non-elderly TS models such as the Fiala dynamic model (Fiala, 1998), the latter demonstrates a steeper TS response to changes in skin temperature, particularly evident at elevated skin temperatures surpassing their neutral value. This underscores a more pronounced decline in perceiving warmth compared to cold stimuli in the elderly, which is supported by empirical evidence (Guergova & Dufour, 2011). The model allows for TS predictions on an ASHRAE 7-point scale (ASHRAE, 2021), ranging from  $-3$  (cool) to  $+3$  (hot), passing through  $0$  (neutral). At steady state, the model predicts elderly TS using the mean skin temperature ( $T_{sk,av}$ ) with the segment weights based on Hardy-Dubois 7-points formula (Hardy et al., 1938). Once  $T_{sk,av}$  is calculated using the bioheat model, elderly TS prediction can be accomplished using Equation (3):

$$= \begin{cases} 3 \tanh \bar{A} 0.425 (\bar{A}_{\bar{A}} - 33.33) & \bar{A}_{\bar{A}} \geq 33.33 \\ 3 \bar{A} \bar{A} \bar{h} \bar{A} 0.275 (\bar{A}_{\bar{A}} - 33.33) & \bar{A}_{\bar{A}} < 33.33 \end{cases} \quad (3)$$

### 2.5.3 A novel cooling chair PCS

Figure 10 presents the proposed chair-microclimate PCS, featuring two symmetric air-supply units placed opposite to each other. Two vents are integrated into each of these units, releasing cool air from an air-conditioning system installed within the chair. The placement of the air-supply units is selected to ensure minimal disruption to seated occupants, and to reduce the influence of their postures on the generated thermal microclimate. Furthermore, positioning is chosen so that only two air-supply units are required to cover the body.



**Figure 10.** Scheme of the proposed elderly chair microclimate PCS.

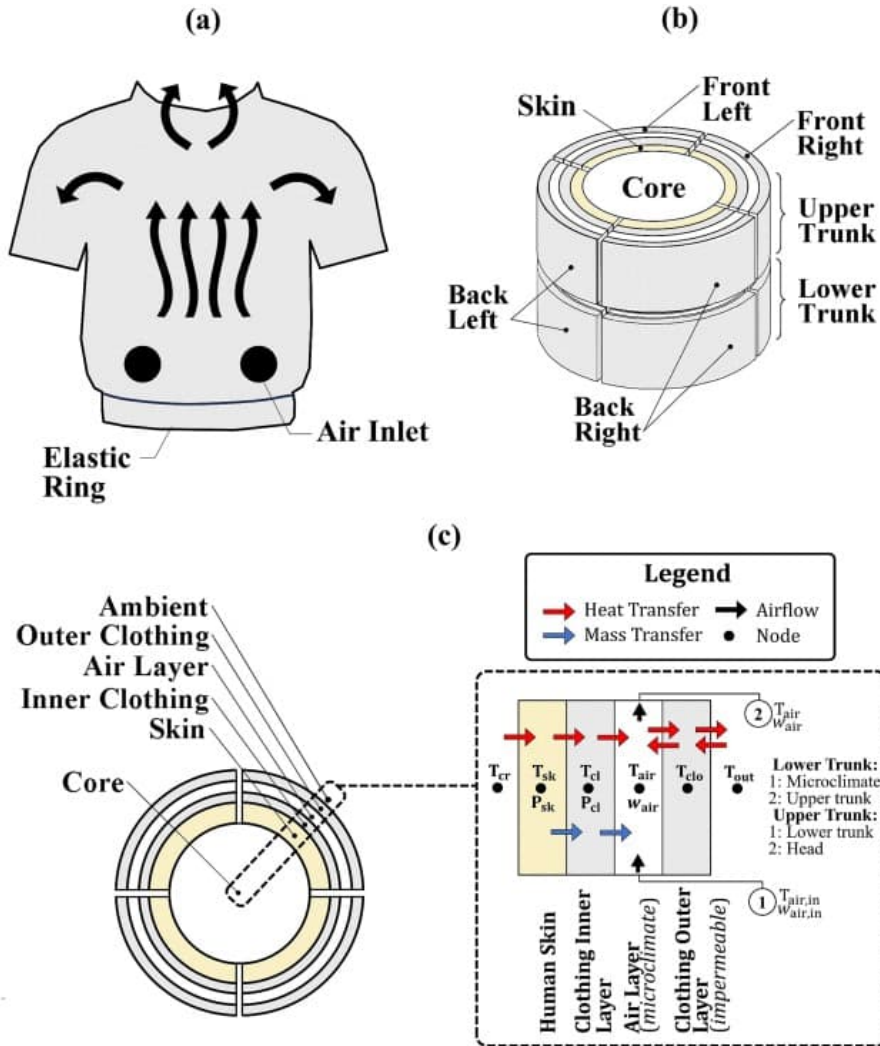
On one hand, lower body vents release cool air above thighs leveraging the difference in air density between released air and background air to establish efficient air confinement. On the other hand, air is released through two symmetric vents in the form of colliding jets that merge to form an upward flow that covers the upper body. These vents are designed with special attention to achieve a successful collision of jets without causing discomfort from drafts. The following design criteria are adopted:

- (1) Attaining microclimate conditions of temperature and air velocity that shift elderly whole-body TS towards thermal neutrality ( $TS \sim 0$ ) in warm room temperatures ( $T_a = 29\text{ }^\circ\text{C}$ ).
- (2) Achieving microclimate conditions of temperature and air velocity that substantially improves elderly whole-body TS in hot room temperatures ( $T_a = 33\text{ }^\circ\text{C}$ ), resulting in TS values below 1.0 as per the ASHRAE 7-point scale.

- (3) Ensuring dissatisfaction from drafts remains under 20 %. Since existing literature demonstrates that age does not influence the perception of draft discomfort (Griefahn & Künemund, 2001), ASHRAE draft discomfort criterion (Toftum et al., 2003) is utilized. Head microclimate air velocity is capped at 0.4 m/s, which corresponds to 20 % dissatisfaction around the desired thermoneutral air temperature of 26 °C.

#### **2.5.4 Ventilated jacket microclimate model**

A one-dimensional model for heat and mass transfer is employed to simulate the ventilated jacket. As shown in Figure 11(a), the model represents the jacket as consisting of an air layer and outer clothing. Figure 11(b) shows the layered arrangement of the jacket when integrated with the bioheat model. The exchange of heat and mass occurring between the body, the jacket, the ventilated air, and the outer surrounding air is presented in Figure 11(c). The equations that describe heat and mass transfer are developed and subsequently utilized for each segment of the trunk. The main inputs to the model are the conditions of skin, ventilated air, and surrounding air; the main outputs are of the conditions of the inner fabric, air layer, and outer fabric. A more detailed description of the calculations can be found in the work of Younes et al (Younes et al., 2024).

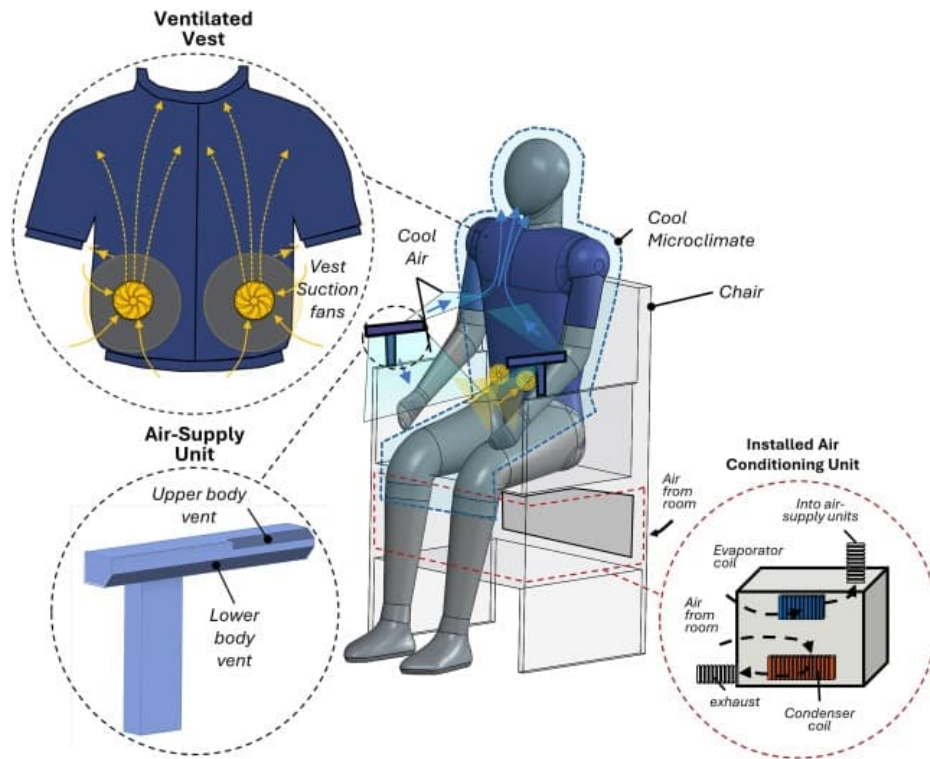


**Figure 11.** Schematic representations of (a) the ventilated jacket showing the airflow (b) bioheat model segments with the added jacket layers (c) heat and mass transfers occurring between the body, the jacket, and the outer environment.

### 2.5.5 Combination of cooling chair system and ventilated jacket

Figure 12 illustrates the concept of the chair microclimate PCS for elderly individuals when combined with a ventilated jacket. The chair-based PCS uses an electrically powered embedded air conditioning system to create a thermal microclimate around the user's body. Conditioned air is delivered through two air supply units symmetrically positioned on the chair armrests. Each unit features two vents: one for supplying air to the lower body and one for the upper body. For the lower body, vents discharge cool air above targeted areas, utilizing the air density

difference between the conditioned and ambient air to effectively confine the cool air around the lower extremities. Air directed at the upper body is supplied from two opposing supply vents, creating an upward airflow that covers the upper body. Two fans are located on the lower area of the jacket covering the frontal trunk. These fans extract and ventilate air through a space between two fabric layers. Air then exits the jacket at low velocity through the neckline and sleeves. This arrangement enables the jacket to actively extract cool air from the microclimate of the chair PCS, and thus, the jacket can function as an “add-on” device to the chair system providing extra cooling during extreme weather, such as heatwaves, when more cooling is needed.



**Figure 12.** Illustration of the proposed chair PCS operation with the ventilated jacket for elderly users in hot conditions.

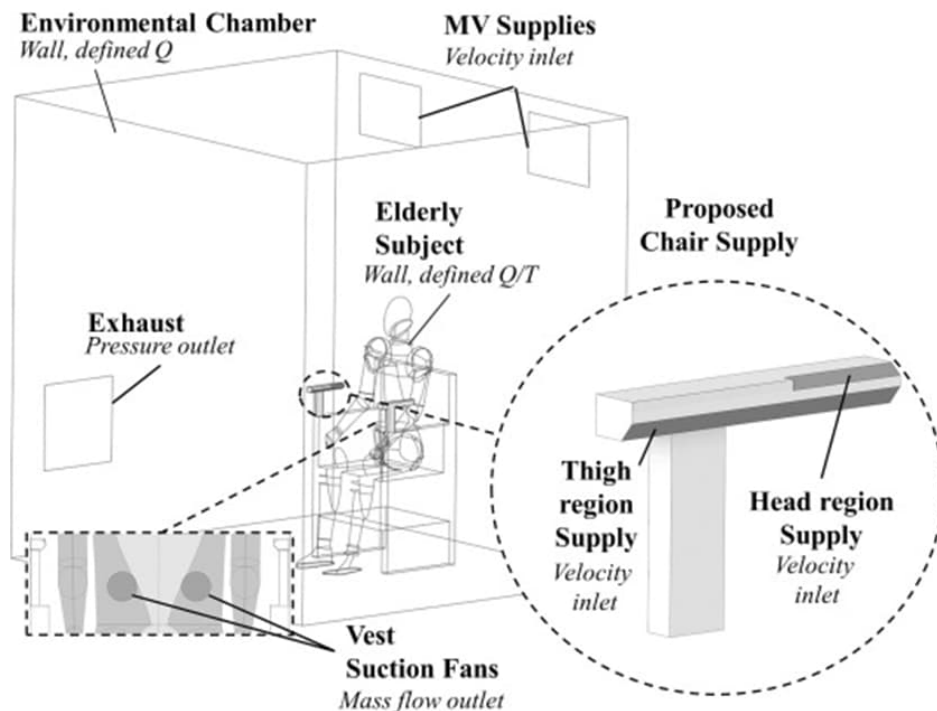
Combining the jacket with the chair system improves trunk heat removal by enabling heat transfer from the skin to the ventilated air through the thin clothing layer. This minimizes thermal resistance compared to the scenario without the jacket, where heat is conducted through multiple clothing and air layers. Additionally, the jacket promotes increased heat transfer by capitalizing on the temperature difference between the skin and the cool ventilated air extracted from the microclimate, while air movement within the air layer amplifies convective heat

transfer mechanisms. The system offers control over thermal microclimate conditions through adjustable supply airflow from the chair and suction airflow from the ventilated jacket. These parameters are controlled aiming to maintain elderly TS near neutrality and prevent sweating discomfort.

### **2.5.6 CFD model of integrated cooling chair system and ventilated jacket**

CFD simulations were used to assess the performance of the chair PCS and ventilated jacket. The simulations were essential for predicting the temperature of ventilated air reaching the jacket during the extraction of microclimate cool air. This prediction was crucial to ensure that the ventilated air temperature aligned with the microclimate temperature, allowing for the assessment of corresponding physiological responses and TS in elderly users. Moreover, CFD simulations played a vital role in understanding the effects of combining the jacket and PCS on microclimate conditions, as well as corresponding TS and energy considerations. Hence, a 3-D CFD simulation tool was employed to solve momentum, energy, pressure velocity coupling, turbulent kinetic energy, and dissipation rate equations. The simulations were executed using the commercial software ANSYS Fluent 2023 R1.

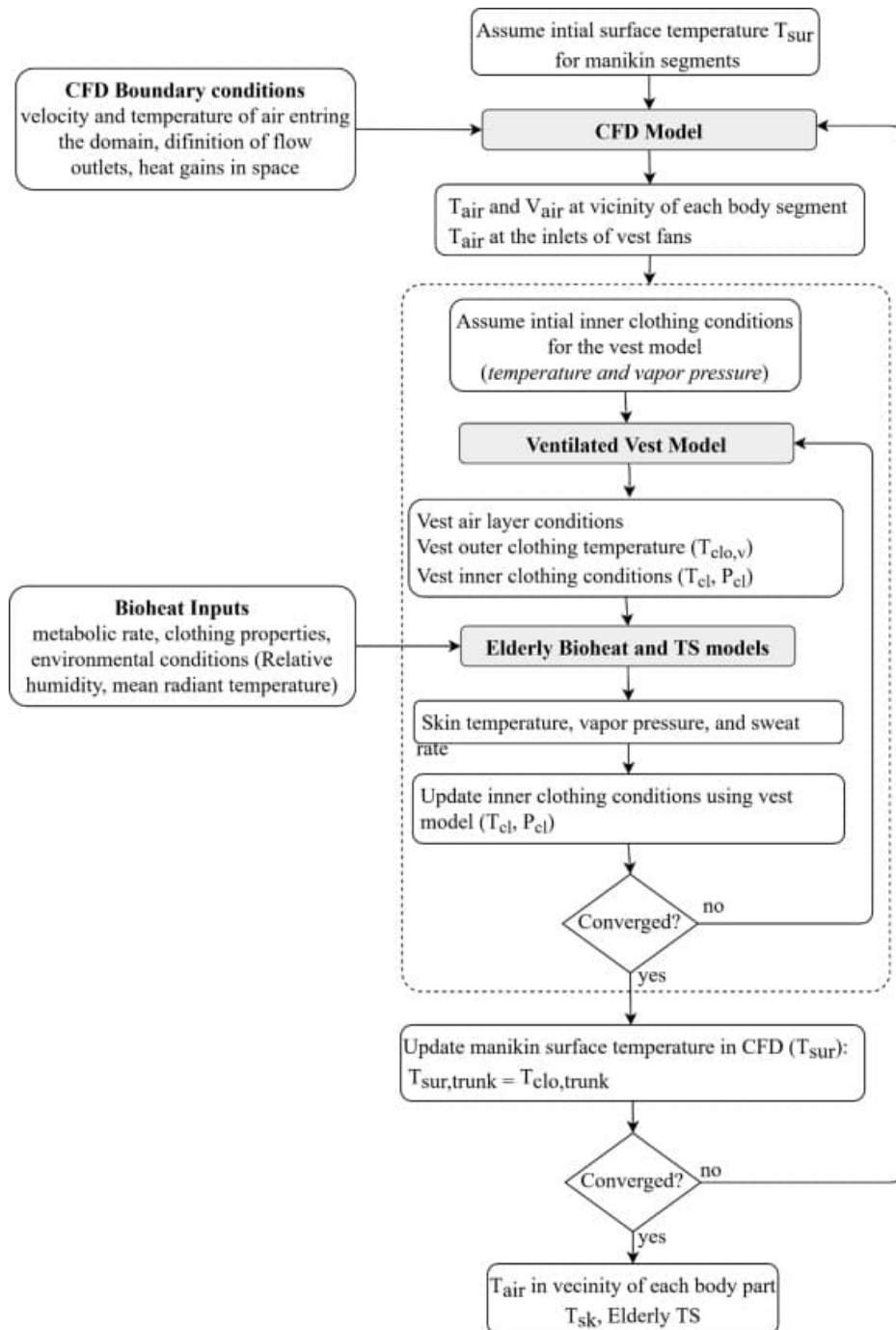
To validate the CFD model, a computational domain was established, including a seated manikin positioned within an environmental chamber, along with the proposed PCS air supply units and jacket suction fans, as shown in Figure 13. This chamber incorporated a mixed ventilation system, consisting of two wall-mounted supply diffusers and one exhaust. The manikin was divided into different sections, such as the head, trunk, arms, hands, thighs, calves, and feet. Its total surface area was around 1.8 m<sup>2</sup>. This area matched the surface area of the physical manikin employed to validate the CFD domain.



**Figure 13.** CFD domain of simulation with boundary conditions

### 2.5.7 Integration of employed models and numerical methods

For accurate prediction of flow and temperature fields in the domain, the CFD model required several boundary conditions, including the surface temperature of the manikin. This was defined as skin temperature for nude segments and as the temperature of the outer clothing layer for clothed segments. In case of the presence of a jacket, the trunk surface temperature was set to the outer jacket layer temperature. Determining skin and clothing temperatures through the bioheat/jacket model in turn required data about air temperature and velocity from the vicinity of each body segment. The bioheat and CFD models were run iteratively until a converging steady state was achieved to solve for these variables within the context of this bidirectional dependency (El-Fil et al., 2016). The procedure began with an initial assumption of surface temperature for manikin segments in the CFD simulation. This assumption allowed the air conditions around each segment to be calculated. The bioheat model then used these conditions to calculate skin and clothing temperatures. These updated temperatures were then used in the CFD model to refine the surface temperature. This iterative process was repeated until the convergence criterion was met.



**Figure 14.** Flow chart of integration of CFD, jacket, and elderly Bioheat models.

The described coupling process applies to all body segments when the ventilated jacket was not in use and to segments other than the trunk when the jacket was worn. In scenarios involving the trunk segment with the jacket, an iterative process involving the bioheat, jacket, and CFD models was employed until a steady state was achieved. In the CFD simulation, the process began with an assumed trunk surface temperature, enabling the calculation of surrounding air conditions and air entering the ventilated jacket. The temperature of the ventilated air corresponds to the average temperature of the air at the ventilated fans surfaces in the CFD; The temperature of the ventilated air was verified to be consistent with the microclimate temperature, particularly in the vicinity of the head and above the thighs. Subsequently, another iterative sequence focused on heat and mass transfer between the jacket and the skin as shown in Figure 14.

The jacket modelling sequence began with initial assumptions of inner clothing temperature and partial vapor pressure, facilitating the use of the jacket model to determine conditions for the air and outer clothing layers. These assumptions enabled the bioheat model to provide skin temperature, vapor pressure, and sweat rate outputs. The bioheat and jacket models were iterated in this sequence until a convergent state was reached for skin, inner fabric, air layer, and outer fabric conditions. The outer fabric temperature was utilized to update the CFD trunk temperature, and the surrounding air and ventilated air conditions were subsequently updated, continuing the iterative procedure between the jacket and bioheat models. Once all models achieved convergence, the simulations were concluded, and results were extracted.

The forward Euler method was used to solve the equations of the bioheat and jacket models with a fixed time step of 0.02 s. Upon achieving convergence of the solution, values of air temperature were extracted from the CFD to assess confinement, while values of skin temperature and TS were extracted to assess the impact of proposed system on elderly individual.

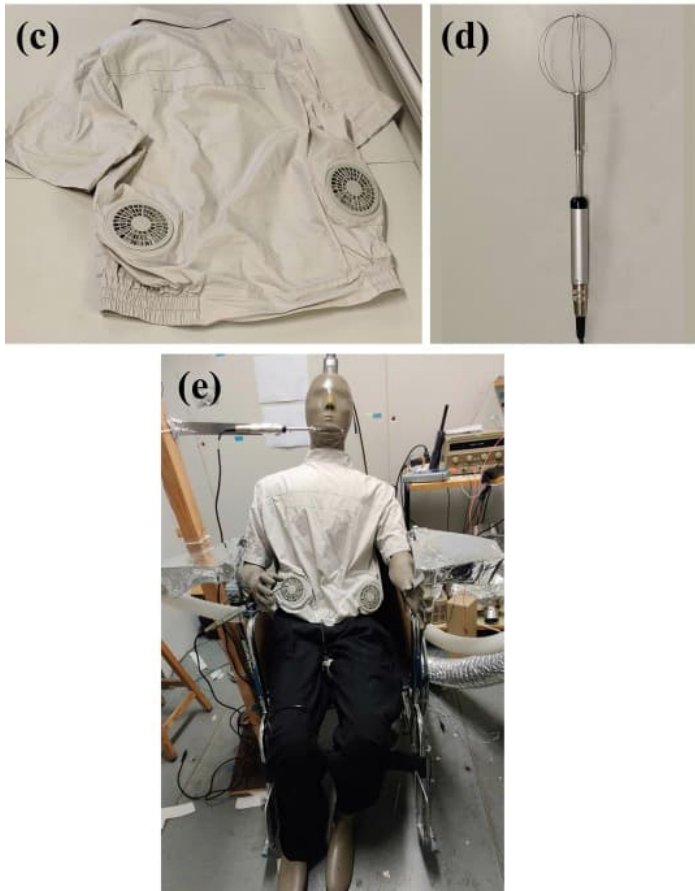
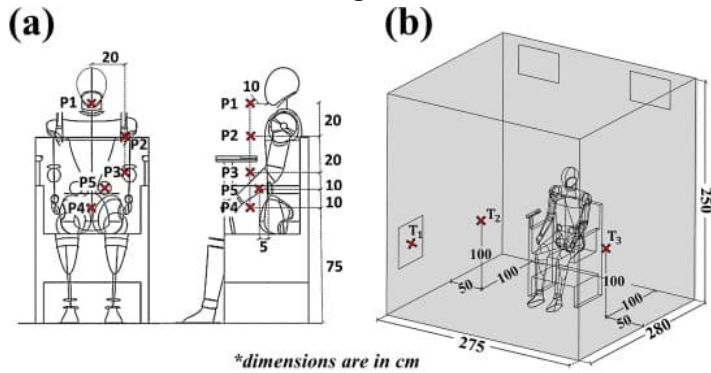
## **2.6 Experimental validation for integrated models**

### **2.6.1 Thermal manikin climate chamber experiments in American University of Beirut**

The main objective of these experiments was to assess the accuracy of the CFD model predictions regarding temperature and airflow and the jacket model regarding the clothing layers and air layer temperatures.

CFD validation involved utilizing a point-measurement approach. This method involved comparing the CFD model-predicted air velocity and temperature values at specific locations within the domain to the measured values to confirm the

accuracy of the CFD model. Sensors measuring both temperature and velocity were positioned at locations P1–P5 (Figure 15(a)).



**Figure 15.** (a) Microclimate sensor positions; (b) Schematic of climatic chamber with macroclimate sensor placement; (c) Ventilated jacket; (d) Omnidirectional anemometer; (e) Thermal manikin in chamber wearing the ventilated jacket.

The climatic chamber utilized for the experiments had inner dimensions of 2.8 m × 2.75 m × 2.5 m. It was equipped with a mixing ventilation system consisting of two identical supply diffusers with a cross-sectional area of 0.57 m × 0.37 m, and an exhaust outlet with a cross-sectional area of 0.524 m × 0.52 m located on the adjacent wall at a height of 0.53 m above the floor (see Figure 15(b)). Microclimate conditions were monitored using three temperature sensors with a measurement accuracy of 0.1 °C at locations T1, T2, and T3. These sensors were provided by Measurement Technologies Northwest.

The “Newton” thermal manikin was employed with “ThermDAC” control software. The manikin had twenty control zones, enabling detailed monitoring and regulation of segmental surface temperature and heat flux. The manikin was seated in a chair equipped with a prototype of the PCS, and the manikin was outfitted with a ventilated jacket composed of a spacer vest liner enclosed by an impermeable outer layer, with two 10 W fans positioned in the lower trunk region, as shown in Figure 15(c). For the inner fabric, it was made of 100 % cotton and had a thickness of 0.6 mm, an area density of 260 g/m<sup>2</sup>, a dry insulation value of 0.019 m<sup>2</sup>·°C/W. An average thickness of 2 cm was used for the air layer gap, without accounting for variations caused by changes in flow rate or flow pattern. As for the outer fabric, it had a thickness of 0.55 mm, a density of 338 g/m<sup>2</sup>, and a dry insulation value of 0.014 m<sup>2</sup>·°C/W.

SWEMA omnidirectional anemometers were used to validate CFD predictions of air speed (velocity magnitude) and air temperature in the chamber (see Figure 15(d)). The air velocity measurement range was 0.05 to 3.0 m/s, with a measurement uncertainty of ±0.03 m/s between 0.05 and 1.0 m/s and ±3 % of the read value between 1.0 and 3.0 m/s. For temperature measurements, the sensor had a measurement range of 10–40 °C and measurement uncertainty of ±0.1 °C. The velocity at the MV diffuser was measured with a SIEMENS QVM62.1 duct velocity sensor, which had a range of 0 to 15 m/s and an accuracy of ± (0.2 m/s + 3 % of the measured value). To validate the predictions of the jacket model, K-type thermocouples, produced by Omega, were employed. The temperatures were measured at the clothing inner layer, air layer, and clothing outer layer using thermocouples. Sensors measuring clothing temperature were attached to clothing and insulated from the second side, while sensors measuring air layer temperature were placed between the inner and outer clothing layers of the jacket. OMEGA DaqPro data logger was utilized for data storage. Given that the system's performance was evaluated under steady conditions, steady-state temperature measurements were compared with clothing and air temperature steady-state predictions by the jacket model.

The temperature of the chamber was maintained at 33 °C ± 0.5 °C, the surface heat flux of the manikin was maintained at 30 ± 0.1 W/m<sup>2</sup>, and velocity at MV diffusers was measured at steady state to be 1 ± 0.23 m/s. The selected heat flux of

30 W/m<sup>2</sup> took into consideration the approximately 21 % lesser metabolic rate of elderly individuals compared to their younger counterparts (Itani et al., 2020). The climatic chamber maintained a relative humidity range of 51 % to 59 % during the experiments. The PCS supply units were adjusted to supply an airflow of  $17 \pm 3$  l/s at a temperature of  $22.0 \text{ }^\circ\text{C} \pm 0.1 \text{ }^\circ\text{C}$  with the upper supply vent air exit velocity maintained at  $1.8 \pm 0.2$  m/s, and the lower vent velocities maintained at  $1.1 \pm 0.2$  m/s. The fans were run at 10 W each and their suction flow rate combined was 11 l/s. The fans were ensured to be symmetrically positioned and to extract same volume of air. Figure 15(e) shows the thermal manikin wearing the ventilated jacket while seated on a chair with the PCS.

The experimental procedure started with the activation of the mixing ventilation system within the climatic chamber at the desired setpoint and continued until a steady state was reached. Then the ventilated jacket was activated, and the temperatures of inner clothing, outer clothing, and air layer were recorded at steady state. After this, the chair PCS was activated while the jacket was still on. When a steady state was reached, the temperatures of the clothing and air layers were recorded again; this time with the values of air temperature and air speed in the locations P1-P5. The thermal manikin surface flux was used as an input in both the CFD and jacket models, and the air velocity at the exit of the chair PCS supply was used as an input to the CFD.

### **2.6.2 Validating the integrated jacket, bioheat and TS models using previous elderly people experimental data**

The main objective was to assess the accuracy of the integrated model. The validation involved two scenarios: one with the jacket off (preconditioning phase in experiment) and the other with the jacket on (cooling phase in experiment).

The validation of physiological response to environmental conditions was performed by comparing the predicted values of mean skin temperature as well as segmental skin temperatures for specific body parts influenced by the jacket with the corresponding measured values. The validated segments encompassed the upper front, upper back, lower front, and lower back regions of the trunk.

In addition to collecting physiological measurements, subjective votes on the overall thermal sensation of elderly people under various conditions were obtained in a previous experiment. The validation procedure was conducted under three distinct environmental conditions, each defined by a specific  $T_a$  and RH and involved a certain number of subjects (N). The conditions and subjects were as follows:  $29 \text{ }^\circ\text{C}/42 \%$ ,  $N = 8$ ;  $32 \text{ }^\circ\text{C}/49 \%$ ,  $N = 12$ ; and  $33 \text{ }^\circ\text{C}/39 \%$ ,  $N = 9$ . The predictions were validated by comparing mean TS values derived from bioheat-predicted mean skin temperature with reported actual subject votes on TS during the experiment.

## 3 Results

This section first shows the results of elderly people's thermal response under warm conditions (**Publication 1,2**), and their physiological and psychological parameter changes before and after using local cooling devices (**Publications 1,2**). Then, the results from the thermal manikin experiment with local cooling devices are reported (**Publication 3**). After that, the relationship between skin temperature, thermal sensation, and device usage of elderly people is introduced (**Publication 2,3**). Finally, the performance of the novelty PCS is explained in detail (**Publication 4**).

### 3.1 Elderly people's thermal response in different thermal environments

In this subsection, the relationship between environmental parameters and elderly people's skin temperature, thermal perception votes, air movement perception votes, and the device-usage power is shown. The differences in thermal response between elderly people of different gender and BMIs are also presented.

#### 3.1.1 Skin temperature change with environmental parameters in uniform steady state

The skin temperature obtained at the end of Phases 1, 3, and 5 (preconditioning and rest phases) in all conditions for all participants was used to analyze the relationship with environmental parameters.  $T_a$  significantly ( $P < 0.05$ ) affected skin temperature, whereas RH had a small effect on it ( $P > 0.05$ ). The linear regressions between  $T_a$  and skin temperature for each local body part are listed in Table 8. The skin temperature of the upper back, forearm, palm, thigh, calf, and foot increased with  $T_a$  faster than that of other body parts, particularly the palm and foot, which had the highest coefficients, whereas the temperature of the pelvis and lower back seemed more stable.

**Table 8.** Linear regression between local skin temperature  $T_{sk}$  of each body part and  $T_a$ .

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Local skin temperature (°C)
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Body parts	$y = aT_a + b$	$R^2$
Forehead	$T_{sk} = 0.291T_a + 26.253$	0.7
Chest	$T_{sk} = 0.276T_a + 26.348$	0.5
Pelvis	$T_{sk} = 0.203T_a + 28.472$	0.1
Upper back	$T_{sk} = 0.369T_a + 23.734$	0.6
Lower back	$T_{sk} = 0.216T_a + 28.749$	0.4
Forearm	$T_{sk} = 0.333T_a + 24.315$	0.6
Palm	$T_{sk} = 0.412T_a + 22.876$	0.6
Thigh	$T_{sk} = 0.344T_a + 23.630$	0.6
Calf	$T_{sk} = 0.328T_a + 23.816$	0.5
Foot	$T_{sk} = 0.451T_a + 19.874$	0.5

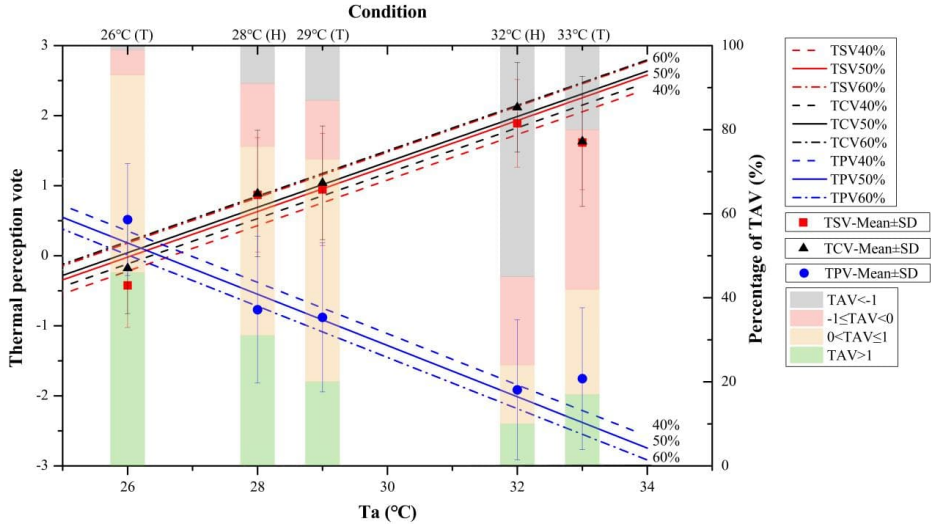
### 3.1.2 Thermal perception and air movement perception change with environmental parameters in uniform steady state

The thermal perception of the elderly was analyzed using thermal comfort votes (TCV), thermal sensation votes (TSV), thermal preference votes (TPV), and thermal acceptance votes (TAV) obtained at the end of Phases 1, 3, and 5 (preconditioning and rest phases) in all conditions for all participants.

Thermal perception was significantly correlated with  $T_a$  and RH ( $p < 0.05$ ), and the linear regression results, which were derived from all individual thermal perception votes in steady phases, as listed in Table 9. Figure 16 illustrates these correlations with distinct lines, and depicts the mean values of TSV, TCV, and TPV in test conditions with distinct dots. When RH was 50%, the  $T_a$  at which TSV=0 was 26.1 °C,  $T_a$  at which TCV=0 was 25.9 °C, and  $T_a$  at which TPV=0 was 26.5 °C. A neutral  $T_a$  of 26 °C was comfortable for the elderly, but they preferred an environment slightly warmer by 0.5 °C. The effect of RH was smaller than that of  $T_a$ . With a 25% increase in RH, TSV, TCV, and TPV changed by approximately 0.5 scales.

**Table 9.** Factors in different formulas under different room air and relative humidity conditions, where  $T_a$  is expressed °C and RH in %.

Thermal response	Linear regression		$R^2$
	Formula		
TCV	$-9.469 + 0.325 \times$	$+ 0.020 \times$	0.54
TSV	$-9.180 + 0.324 \times$	$+ 0.016 \times$	0.51



**Figure 16.** Thermal perception under the five warm conditions.

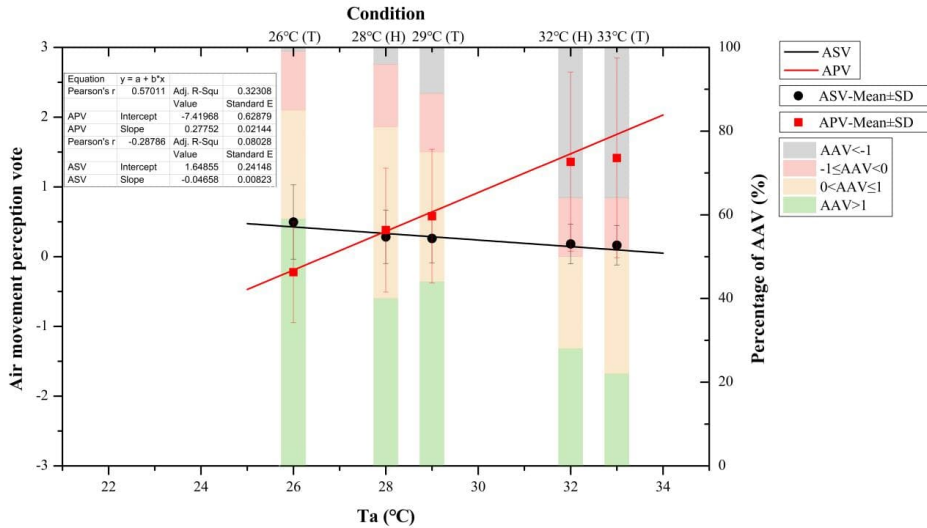
The absolute values of TSV, TCV, and TPV at 33 °C (T) were lower than those at 32 °C (H) (Figure 16). It was speculated in this study that this may be caused by a change in the main heat dissipation method. Sensible heat dissipation was the main method for elderly people when the  $T_a$  was approximately 29 °C. As  $T_a$  increased, sensible heat dissipation weakened, and the primary mode of heat dissipation may have shifted to evaporative heat dissipation (visible and latent sweat evaporation). Temperature of 32 °C (H) had a higher RH of 50%, whereas 33 °C (T) had 40%. When the ambient temperature or water vapor pressure exceeds a threshold, evaporative heat dissipation of the human body increases rapidly, which might slow overall heat dissipation (Berglund & Gonzalez, 1977).

Figure 16 depicts the TAV proportion in the various ranges ( $TAV > 1$ ,  $0 < TAV \leq 1$ ,  $-1 \leq TAV < 0$ , and  $TAV < -1$ ) using stacked columns. If we regard TAV ranging between 0 and 3 as representing feelings of “acceptable”, then the proportion of participants who accepted the thermal conditions at 26 °C (T), 28 °C (H), 29 °C (T), 32 °C (H), and 33 °C (T) was 93%, 76%, 73%, 24%, and 42%, respectively, indicating that a combination of high  $T_a$  and high RH was less acceptable for the elderly. The environment was generally considered to be satisfactory when approximately 80% or more of the occupants accept the environment (ASHRAE, 2021). Thus, the upper limit  $T_a$  accepted by the elderly in this study was approximately 28 °C.

The air movement perception of the elderly was analyzed using air movement sensation vote (ASV), air movement preference vote (APV), and air movement

acceptance vote (AAV) obtained at the end of Phases 1, 3, and 5 (preconditioning and rest phases) in all conditions for all participants.

Air movement perception was significantly correlated with  $T_a$  ( $p < 0.01$ ) (Figure 17). An increase in  $T_a$  decreased ASV and increased APV. When  $APV = 0$ , ASV was 0.4, and  $T_a$  was 26.7 °C. This suggests that the elderly preferred more air movement when the  $T_a$  increased, and an almost “no air movement” sensation in a neutral environment.



**Figure 17.** Air movement perception under the five warm conditions.

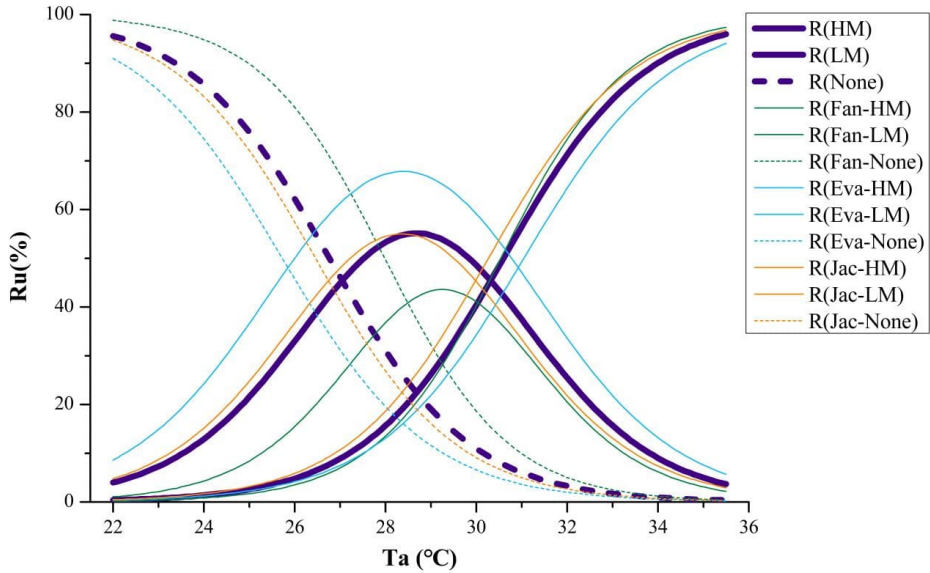
At 26 °C (T), 28 °C (H), 29 °C (T), 32 °C (H), and 33 °C (T), the proportion of participants who accepted the air movement ( $AAV > 0$ ) was 85%, 81%, 75%, 50%, and 52%, respectively. With the same criteria as thermal acceptance, the upper limit of the acceptable  $T_a$  was approximately 28 °C.

### 3.1.3 Device-usage change with environmental parameters in non-uniform steady state

The device use rate (R) in the end of Phases 2, 4, and 6 (local cooling phases) was used to describe the behavior of the elderly. R was defined as the ratio of the number of participants currently using a device to the total number of participants.

The table fan had two speeds: F50% and F100%. The evaporative cooling device had 10 speeds, E10% to E100%, at 10% intervals. The jacket had four speeds, J25% to J100%, at 25% intervals. F50%, E10–50%, and J25–50% were considered the lower modes (LM) whereas F100%, E50–100%, and J75–100% were the higher

modes (HM). Ordinal regression analysis was used to investigate the relationship between  $R$  and  $T_a$  (Figure 18 and Table 10).



**Figure 18.** Device usage model as a function of the room air temperature.

The device usage model was defined as follows:

$$(HM) = \frac{1}{1 + \exp^{-\alpha_1 + \beta \cdot Ta}} \quad (4)$$

$$(LM) = \frac{1}{1 + \exp^{-\alpha_2 + \beta \cdot Ta}} - (HM) \quad (5)$$

$$(None) = 1 - (HM) - (LM), \quad (6)$$

where  $R$  is the use rate of the different modes,  $\alpha$  is the constant of the ordinal regression equation,  $\beta$  is the regression coefficient, ( $\alpha$ ,  $\beta$  are listed in Table 10), and  $T_a$  is the room air temperature ( $^{\circ}\text{C}$ ).

**Table 10.** Factors in device usage models for individual devices and average.

Device	Factors of device-use model			Nagelkerke's pseudo $R^2$
	$\alpha_1$	$\alpha_2$	$\beta$	
All devices	-20.190	-17.556	0.655	0.61
Table fan	-22.324	-20.456	0.731	0.78

Evaporative cooling device	-21.270	-17.383	0.674	0.80
Air-cooled jacket	-19.674	-17.199	0.650	0.74

Figure 18 illustrates the usage model of all three devices and the average usage of all local cooling devices. As we expected, R increased with the  $T_a$ , whereas RH had no significant ( $p > 0.05$ ) effect on R. R was 50% at 26.8 °C. As  $T_a$  increased, the use of LM increased initially and subsequently decreased, whereas the use of HM increased. When  $T_a$  was at 28.7 °C, the use rate of LM was at its highest at 55%. When  $T_a > 30.4$  °C, the use rate of HM was greater than that of LM. The R values of the different devices varied slightly. For the table fan, evaporative cooling device, and air-cooled jacket, the  $T_a$  corresponding to  $R=50\%$  was 28.0 °C, 25.7 °C, and 26.5 °C, respectively. The  $T_a$  corresponding to the highest LM use rate was 29.3 °C, 28.4 °C, and 28.4 °C, respectively. The  $T_a$  corresponding to when the use rate of HM became greater than that of LM was 30.1 °C, 31.0 °C, and 30.0 °C, respectively.

Generally, despite differences between devices, when  $T_a$  was higher than the preferred temperature and reached 27 °C, R was approximately 50%, and LM was mainly used. When  $T_a$  was close to the upper limit at 28 °C, the LM use rate was highest at approximately 60%. As  $T_a$  increased to 30.5 °C, the HM use rate eventually surpassed LM.

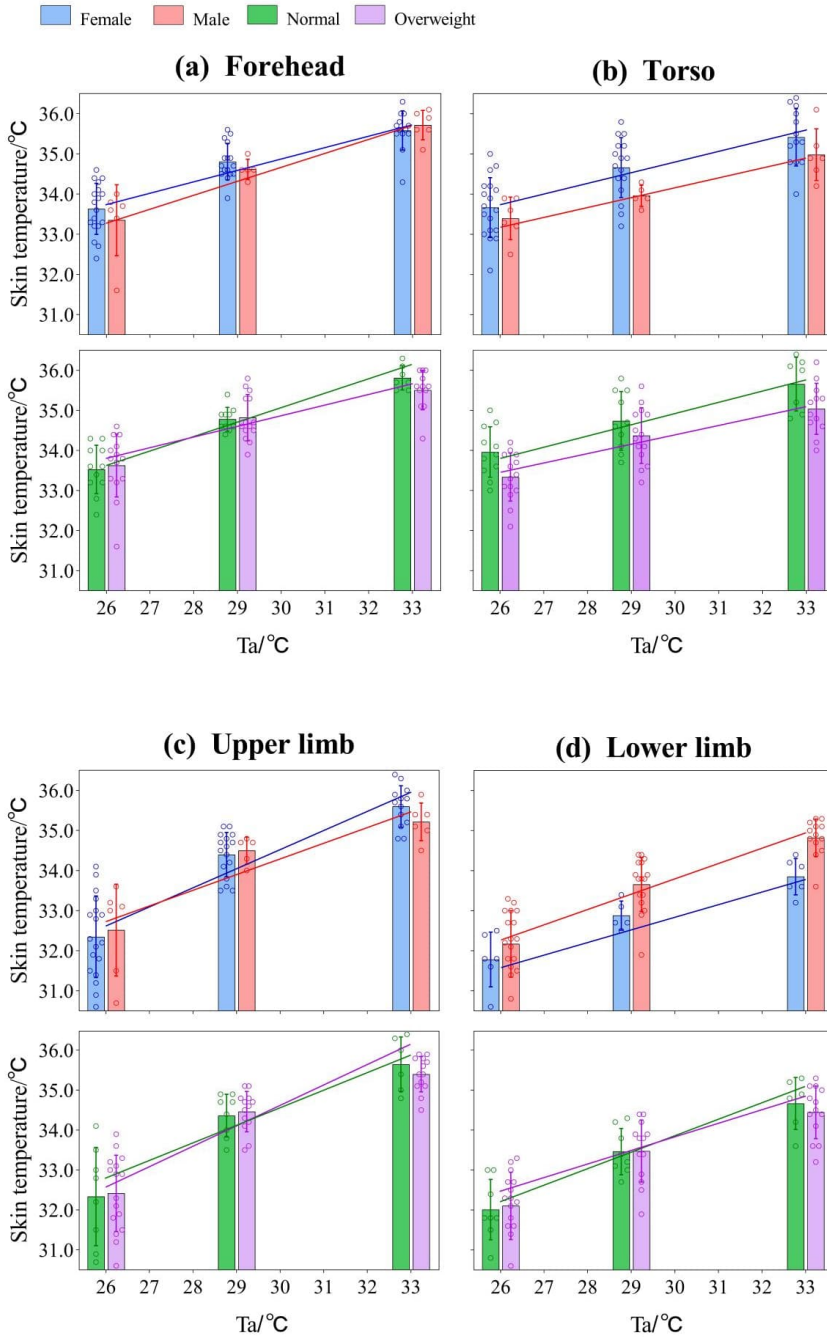
### 3.1.4 Effects of gender and BMI on thermal response

This section aims to quantify the effect of gender and BMI on physiological responses (skin temperature and core temperature), psychological responses (thermal sensation and thermal preference), and control of the device (average device usage power) as ambient  $T_a$  increases, using Formula (2). The 26 participants were divided into 19 females and 7 males, and 12 normal and 14 overweight participants according to BMI (Table 6). To eliminate the potential confounding effects of RH, we only utilized data from conditions where RH was constant, including 26 °C/40% RH, 29 °C/40% RH, and 33 °C/40% RH.

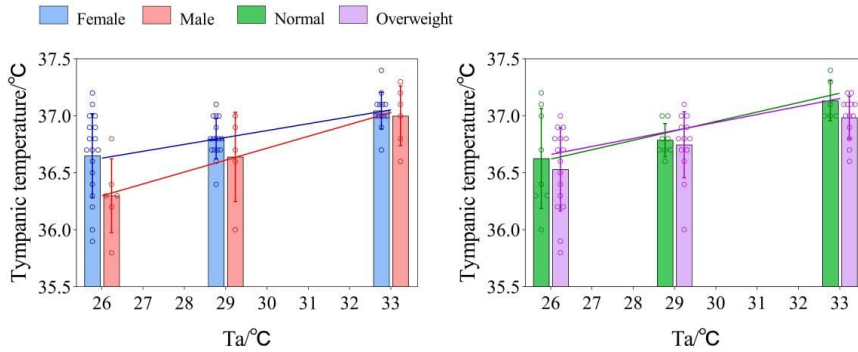
#### 3.1.4.1 Effects of gender and BMI on physiological parameters

Figure 19 and 20, respectively, show the results obtained from the analysis of the skin and tympanic temperature data during the steady state of the rest phase. Figure 19 depicts the skin temperatures in the four body regions (head, torso, upper limbs, and lower limbs) for different gender (blue = female, red = male) and BMI groups (green = normal weight, purple = overweight). Each point represents a sample, and bar charts indicate the mean values for each group. The lines represent the regression outcomes for the male (blue), female (red), normal (green), and

overweight (purple) groups. Tables 11 and 12 detail the numerical results from the regression analysis.



**Figure 19.** Skin temperature distribution in different groups.



**Figure 20.** Tympanic temperature distribution in different groups.

**Table 11.** Regression results of skin temperature.

Difference in skin temperature based on gender and BMI						
Body part	Gender			BMI		
	Coefficient	P> t	R <sup>2</sup>	Coefficient	P> t	R <sup>2</sup>
Forehead	a1	26.48	0.00	a2	24.26	0.00
	b1	-1.98	0.54	b2	2.50	0.29
	c1	0.28	0.00	c2	0.36	0.00
	d1	0.06	0.88	d2	-0.09	0.51
Torso	a1	27.02	0.00	a2	26.52	0.00
	b1	-0.05	0.01	b2	0.98	0.08
	c1	0.26	0.00	c2	0.28	0.00
	d1	-0.02	0.39	d2	-0.05	0.19
Upper limb	a1	20.12	0.00	a2	19.32	0.00
	b1	2.16	0.86	b2	2.03	0.79
	c1	0.48	0.00	c2	0.51	0.00
	d1	-0.08	0.61	d2	-0.07	0.78
Lower limb	a1	23.55	0.00	a2	21.56	0.00
	b1	-1.14	0.00	b2	2.07	0.78
	c1	0.31	0.00	c2	0.41	0.00
	d1	0.07	0.14	d2	-0.07	0.72

a<sup>1</sup>: Intercept for female

a<sup>2</sup>: Intercept for normal

b<sup>1</sup>: Intercept difference

b<sup>2</sup>: Intercept difference

c<sup>1</sup>: Slope for female

c<sup>2</sup>: Slope for normal

d<sup>1</sup>: Slope difference

d<sup>2</sup>: Slope difference

**Table 12.** Regression results of tympanic temperature.

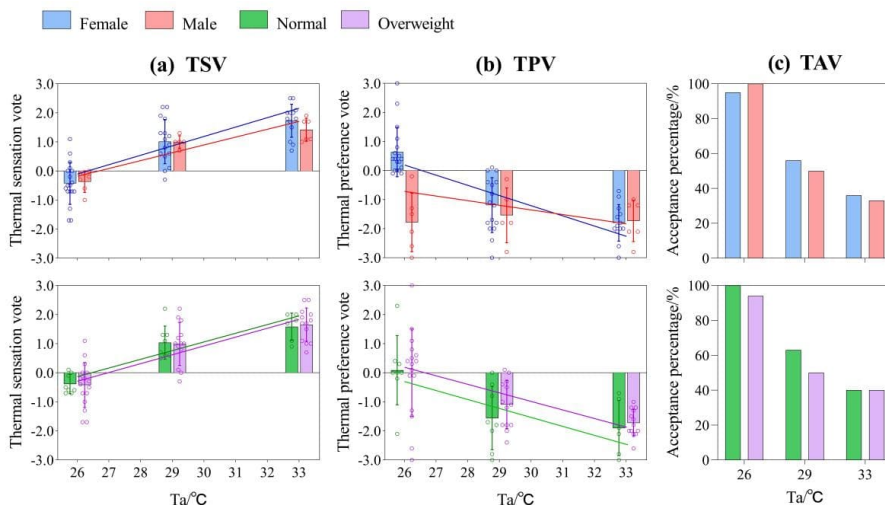
Difference in tympanic temperature based on gender and BMI				
		Coefficient	P> t	R <sup>2</sup>
Gender	a: Intercept for female	35.07	0.00	0.42
	b: Intercept difference	-1.5	0.04	
	c: Slope for female	0.06	0.01	
	d: Slope difference	0.04	0.05	
BMI	a: Intercept for normal	34.56	0.00	0.34
	b: Intercept difference	0.28	0.63	
	c: Slope for normal	0.08	0.00	
	d: Slope difference	-0.01	0.58	

There were no significant ( $P > 0.05$ ) differences in intercepts and slopes for head and upper limb skin temperatures between females and males ( $P > 0.05$ ), indicating that these temperatures were similar in both the neutral (26 °C) and warm (33 °C) conditions. However, there were significant ( $P < 0.05$ ) differences in the intercepts for the torso and lower limb skin temperatures, whereas there were no significant differences in the slopes, suggesting that these temperature differences existed under neutral conditions and remained almost constant as the temperature rose. Specifically, females had 0.6 °C higher torso temperatures and 0.9 °C lower limb temperatures than males. Between the normal and overweight groups, only torso skin temperature showed a significant difference, with the normal group being 0.7 °C higher at 33 °C. The intercepts and slopes of skin temperatures in other regions were similar.

There were significant differences in both the intercept and slope of the tympanic temperature between females and males. In a neutral condition (26 °C), females had a tympanic temperature that was 0.5 °C higher than that of males. However, as the temperature increased, the tympanic temperature of males rose more rapidly, resulting in nearly identical tympanic temperatures between the two groups in a warm condition (33 °C). For the normal weight and overweight groups, there were no significant differences in either the intercepts or slopes of tympanic temperature (the normal weight group was 0.1 °C higher than the overweight group).

### 3.1.4.2 Effects of gender and BMI on psychological parameters

The analysis of the TSV and TPV during the steady state of the rest phase yielded the results shown in Figure 21(a) and Figure 21(b), respectively. Table 13 presents detailed regression results. The TSV intercept for females and males was similar, whereas the slope for females was slightly higher than that for males (no significant difference), resulting in a similar TSV for both gender at 26 °C, with females having a 0.4 higher TSV than males at 33 °C. No significant differences in intercepts or slopes could be found between the normal and overweight groups.



**Figure 21.** Distributions of TSV, TPV, and acceptance percentage in different groups.

**Table 13.** Regression results of skin temperature.

Differences in TSV and TPV based on gender and BMI							
	Gender			BMI			
	Coefficient	P> t	R <sup>2</sup>	Coefficient	P> t	R <sup>2</sup>	
TSV	a <sup>1</sup>	-8.41	0.00	a <sup>2</sup>	-7.94	0.00	0.61
	b <sup>1</sup>	1.21	0.81	b <sup>2</sup>	-0.13	0.90	
	c <sup>1</sup>	0.32	0.00	c <sup>2</sup>	0.30	0.00	
	d <sup>1</sup>	-0.05	0.80	d <sup>2</sup>	0.00	0.91	
TPV	a <sup>1</sup>	9.29	0.00	a <sup>2</sup>	7.75	0.00	0.60
	b <sup>1</sup>	-10.94	0.36	b <sup>2</sup>	0.34	1.40	
	c <sup>1</sup>	-0.35	0.00	c <sup>2</sup>	-0.31	0.00	
	d <sup>1</sup>	0.34	0.02	d <sup>2</sup>	0.00	0.05	

a<sup>1</sup>: Intercept for female

a<sup>2</sup>: Intercept for normal

b<sup>1</sup>: Intercept difference

b<sup>2</sup>: Intercept difference

c<sup>1</sup>: Slope for female

c<sup>2</sup>: Slope for normal

d<sup>1</sup>: Slope difference

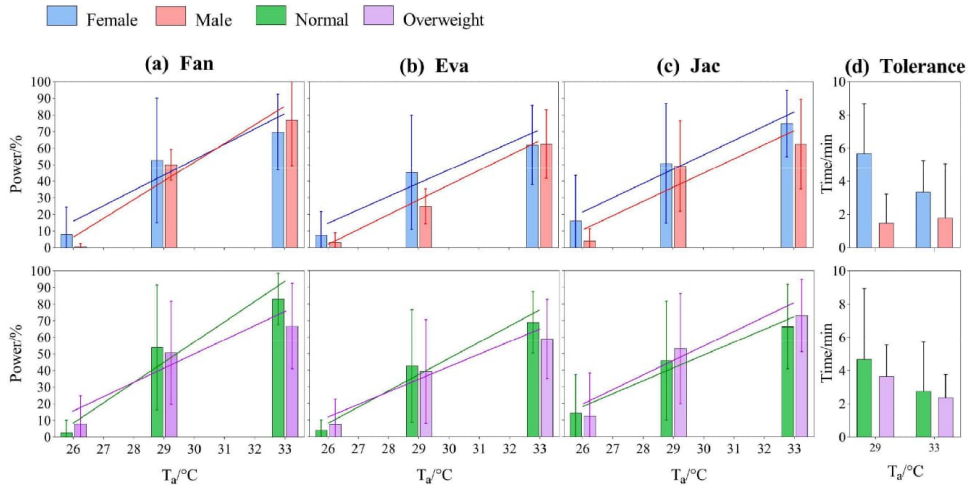
d<sup>2</sup>: Slope difference

At 26 °C, the TPV for males was 1.8 lower than that for females, indicating that females preferred a warmer environment while males preferred a cooler one. However, as temperature increased, the slope of the TPV for females was significantly greater than that for males, leading to nearly identical thermal preferences at 33 °C. The normal and overweight groups had equal slopes, suggesting that the TPV of the normal group was 0.3 lower than that of the overweight group across all conditions. Although the differences between groups existed, they were not statistically significant. This lack of significance may be attributed to the substantial within-group variance in TPV as denoted by the variance and sample distribution (Figure 21(b)). This implies that, as a subjective perception, thermal preference exhibits greater individual differences than thermal sensation.

The TAV was also analyzed during the steady state of the rest phase.  $TAV \geq 0$  was considered to indicate acceptance of the current thermal environment, whereas  $TAV < 0$  suggested non-acceptance. As shown in Figure 21(c), the acceptance rates varied across the different conditions according to gender and BMI. At 26 °C, nearly all participants accepted the current thermal environment. However, at 29 °C and 33 °C, females exhibited a higher acceptance rate than males, and the normal group had a higher acceptance rate than the overweight group. This implies that females and individuals with a normal BMI are more tolerant and accept a warm environment.

### 3.1.4.3 Effects of gender and BMI on control of the device

An analysis of the average power usage during the local cooling phase for the table fan (Fan), evaporative cooling device (Eva), and air-cooled jacket (Jac) yielded the results displayed in Figure 22(a), (b), and (c), respectively. Table 14 presents detailed regression outcomes. At 26 °C, most participants did not use local cooling devices. At 29 °C and 33 °C, the average power usage for the table fan was similar between females and males, whereas females used about 10% higher power with the evaporative cooling device and air-cooled jacket compared to males. The normal weight group used approximately 15% more power with the table fan and evaporative cooling device than the overweight group, whereas the overweight group used around 10% more power with the air-cooled jacket than the normal weight group. Similarly to the TPV results, despite differences in the average power usage across conditions and groups, the intercepts and slopes were not statistically significant, reflecting substantial individual variability in device usage.



**Figure 22.** Distribution of average usage power for the three devices.

**Table 14.** Regression results of average power usage of the three devices.

Difference in usage power of the devices based on gender and BMI							
Device	Gender			BMI			
	Coefficient	P> t	R <sup>2</sup>	Coefficient	P> t	R <sup>2</sup>	
Fan	a <sup>1</sup>	-224.16	0.00	a <sup>2</sup>	-308.64	0.00	0.44
	b <sup>1</sup>	-62.18	0.70	b <sup>2</sup>	99.77	0.88	
	c <sup>1</sup>	9.23	0.00	c <sup>2</sup>	12.20	0.00	
	d <sup>1</sup>	2.02	0.40	d <sup>2</sup>	-3.58	0.66	
Eva	a <sup>1</sup>	-196.94	0.00	a <sup>2</sup>	-245.74	0.00	0.46
	b <sup>1</sup>	-31.61	0.46	b <sup>2</sup>	63.39	0.74	
	c <sup>1</sup>	8.11	0.00	c <sup>2</sup>	9.76	0.00	
	d <sup>1</sup>	0.76	0.12	d <sup>2</sup>	-2.27	0.60	
Jac	a <sup>1</sup>	-203.50	0.00	a <sup>2</sup>	-183.76	0.00	0.45
	b <sup>1</sup>	-8.60	0.59	b <sup>2</sup>	-25.56	0.65	
	c <sup>1</sup>	8.64	0.00	c <sup>2</sup>	7.76	0.00	
	d <sup>1</sup>	-0.08	0.64	d <sup>2</sup>	1.03	0.54	

a<sup>1</sup>: Intercept for female

a<sup>2</sup>: Intercept for normal

b<sup>1</sup>: Intercept difference

b<sup>2</sup>: Intercept difference

c<sup>1</sup>: Slope for female

c<sup>2</sup>: Slope for normal

d<sup>1</sup>: Slope difference

d<sup>2</sup>: Slope difference

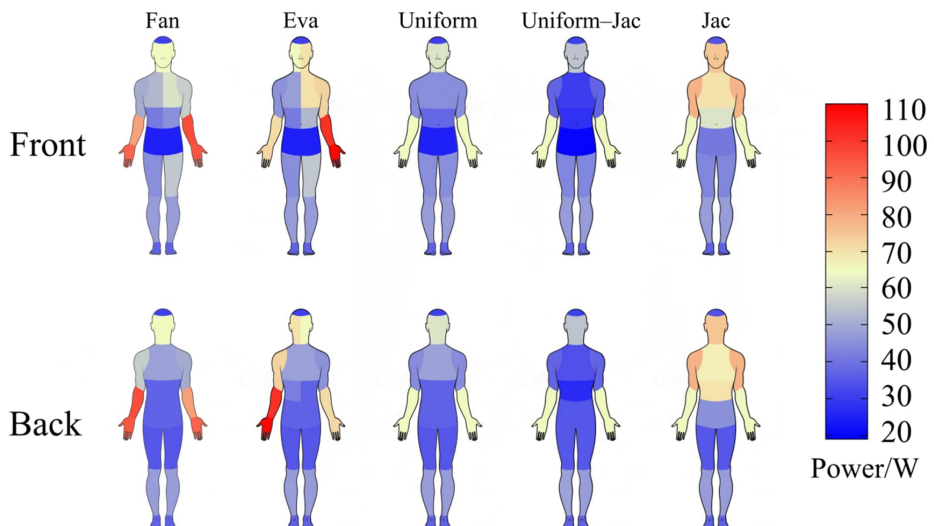
In this section the duration from the start of the local cooling phase to the first activation of the cooling devices (taking the average of the three devices) was also analyzed and Fig. 22(d) portrays the results. At 29 °C and 32 °C, females had a longer duration than males, and the normal group had a longer duration than the overweight group. This duration reflects thermal endurance, indicating that females and the normal BMI group had greater thermal tolerance than males and the overweight group. This finding aligns with a previous analysis of thermal acceptance, denoting that females and the normal BMI group were more accepting of the thermal environment, thereby exhibiting longer endurance times.

### 3.2 The effectiveness of different local cooling PCS under warm conditions

In this subsection the focus is on presenting the results from the thermal manikin test, including the exposed body parts when using local cooling device and the equivalent temperature generated by the device. The difference in elderly people’s thermal response before and after using the device is also shown here.

#### 3.2.1 Body parts exposed to local cooling in thermal manikin test

Figure 23 shows the electricity consumption of 27 manikin segments at 26 °C/40% RH in five cases: no local cooling device used, air-cooled jacket worn but not used, and after using the table fan, evaporative cooling device, and air-cooled jacket at their maximum power.



**Figure 23.** Electricity consumption of heating element of each segment of thermal manikin under different cases (Fan, table fan; Eva, evaporative cooling device; Uniform, no local cooling device used; Uniform-Jac, air-cooled jacket was worn but not used; Jac, air-cooled jacket).

After using a table fan or an evaporative cooling device, the heat loss (directly proportional to electricity consumption) of the chest, upper arm, forearm, and hand increased substantially compared to the situation without them. This suggests that, as intended, the airflow generated by these devices placed on the table mainly acted on the torso (chest) and limbs. The heat loss of the head and thigh also increased, indicating that they were also influenced by the airflow. As a result of the additional clothing insulation provided by the air-cooled jacket, the heat loss of the chest, back, and upper arm was reduced when the air-cooled jacket was worn without being used compared to when it was not worn. The use of an air-cooled jacket substantially cooled the chest, back, and upper arms. Heat loss from the head also increased, possibly because the airflow released from the collar affected the head.

### 3.2.2 Equivalent temperature for three local cooling devices

Table 15 lists the overall equivalent temperatures ( $T_{eq}$ ), which were calculated using Formula (1), at different speeds of the three local cooling devices under different conditions.

**Table 15.** Overall equivalent temperature of the three local cooling devices.

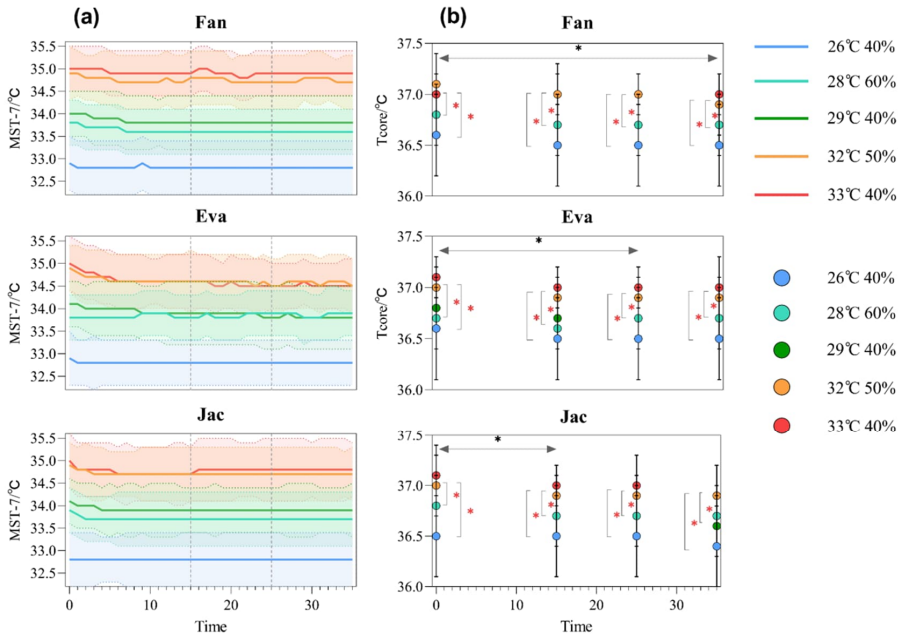
Device	Power (%)	Speed (mode)	$T_{eq}$ under three conditions (°C)		
			26 °C/40%	29 °C/40%	32 °C/40%
Table fan	50 %	1	24.8	28.3	31.9
	100 %	2	24.7	28.1	31.7
Eva	10 %	1	25.4	28.8	31.4
	20 %	2	25.3	28.6	31.3
	30 %	3	25.3	28.5	31.2
	40 %	4	25.2	28.3	31.1
	50 %	5	25.1	28.1	31
	60 %	6	24.9	27.8	30.8
Evaporative cooling device	70 %	7	24.9	27.7	30.8
	80 %	8	24.8	27.5	30.7
	90 %	9	24.7	27.3	30.6
	100 %	10	24.7	27.2	30.5
Air-cooled jacket	0 %	0	27	29.8	32.4
	25 %	1	24.9	28.4	31.6
	50 %	2	24.2	27.8	31.3

75 %	3	23.9	27.7	31.3
100 %	4	23.5	27.4	31.2

Although the three selected devices have similar electrical power, Table 15 shows that their objective effects differ. The table fan provided the narrowest range of  $T_{eq}$  (28.1–28.3 °C at 29 °C and 31.7–31.9 °C at 32 °C), followed by the air-cooled jacket (27.4–28.4 °C at 29 °C and 31.3–31.6 °C at 32 °C). The evaporative cooling device offered the widest  $T_{eq}$  range (27.2–28.8 °C at 29 °C and 30.5–31.4 °C at 32 °C). At both 28 °C and 32 °C, the evaporative cooling device achieved the lowest  $T_{eq}$  among the three devices, followed by the air-cooled jacket, with the table fan providing the highest  $T_{eq}$ . Table 15 also provides additional information; When wearing the air-cooled jacket without using it,  $T_{eq}$  reached 29.8 °C in the 29 °C condition and 32.4 °C in the 32 °C condition, reflecting the jacket’s inherent clothing insulation (around 0.19 clo).

### 3.2.3 Changes of mean skin temperature and core temperature during local cooling phase

The changes in mean skin temperature (MST) and core temperature ( $T_{core}$ , represented by tympanic temperature) in uniform (only include measurements at the end of uniform phases) and non-uniform state were examined in this study. The MST was calculated using the Dubois 7-point method. The data (average for all participants) were examined using repeated-measures ANOVA. Figure 24(a) shows the changes in the MST in uniform ( $t=0$  min) and non-uniform state. Different colors represent different test conditions, and the shaded areas represent the 5th and 95th percentiles of the standard deviations in Figure 24(a). MST changed primarily during the first 10 min. In this period, significant ( $P<0.05$ ) drops of MST could be found in all cases except when using the table fan in 33 °C/40% RH and the evaporative cooling device in 28 °C/60% RH. After 10 min, only minor fluctuations were observed. After using any of the three devices, the MST decreased by less than 0.5 °C.



**Figure 24.** (a) Trends of the mean skin temperature; (b) core temperature under different conditions with local cooling devices. (Fan, table fan; Eva, evaporative cooling device; Jac, air-cooled jacket.)

Figure 24(b) shows the core temperature measured at four timepoints: at the end of the uniform condition ( $t = 0$  min) and under nonuniform conditions at  $t = 15$ , 25, and 35 min. The core temperature after using the local cooling device was significantly lower ( $P < 0.05$ ) than that under the uniform condition. However, no significant ( $P > 0.05$ ) differences were found among the three measurements ( $t = 15$ , 25, and 35 min) during the local cooling phase, indicating that the core temperature changed very slowly and could be considered stable. Thus, combined with the result that MST tended to be stable after 10 min in the local cooling phase, the physiological parameters at the end of the local cooling phase ( $t = 35$  min) can be considered approximately stable.

Figure 24 also shows that the MST and core temperatures were significantly ( $P < 0.05$ ) different for neutral, slightly warm, and warm conditions. For example, the use of local cooling devices in slightly warm conditions did not lower the MST and core temperatures to their level in the neutral condition. This indicates that the effect of local cooling devices on these physiological parameters was limited.

### 3.2.4 Variation of local skin temperature before and after use of local cooling devices

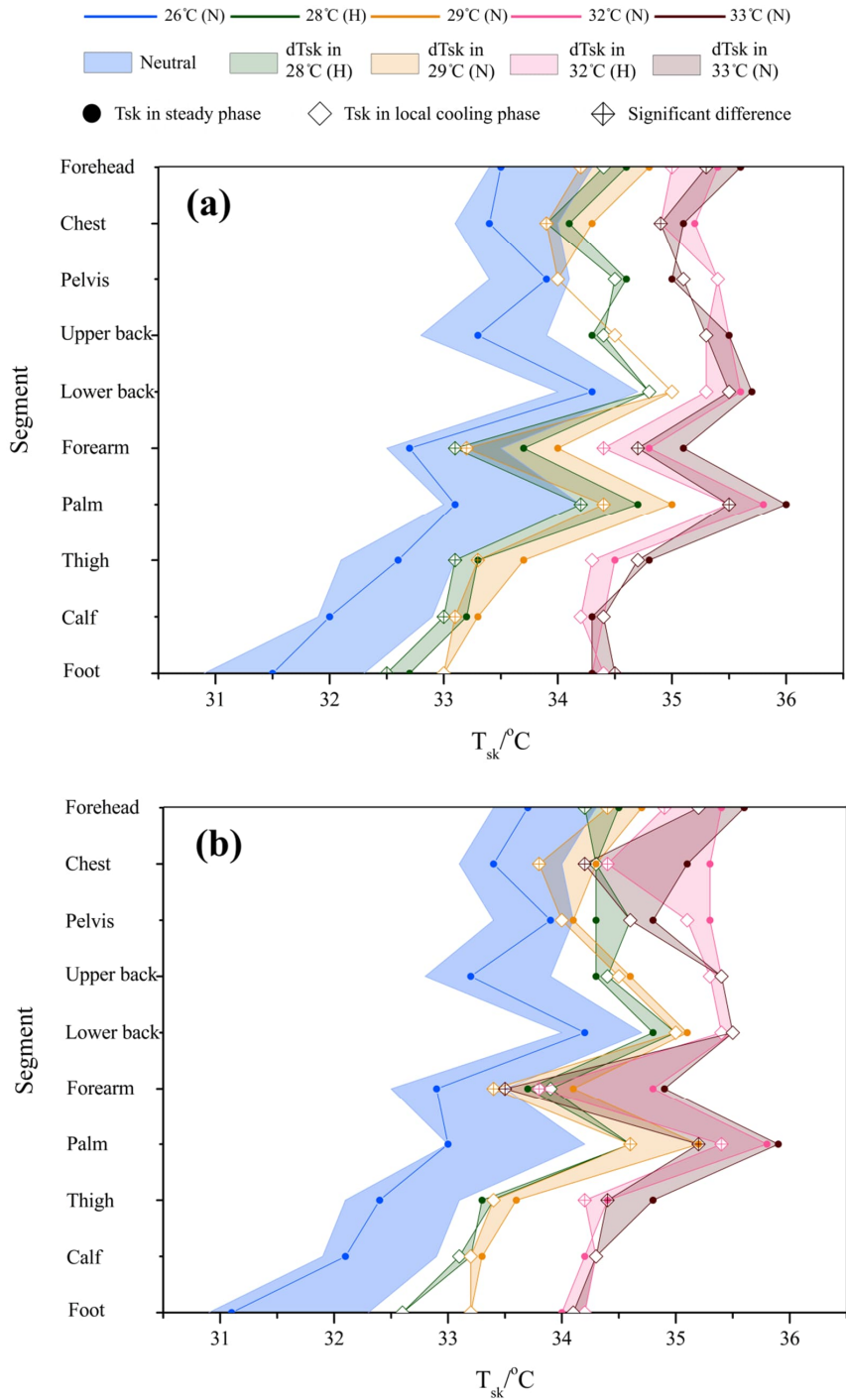
Firstly, the neutral  $T_a$  range ( $24.5\text{ }^\circ\text{C} < T_a < 27.6\text{ }^\circ\text{C}$ ) of elderly people with 0.5 clo obtained from Table 9 was used to calculate the lower and upper limits of the neutral skin temperature of each body part using the corresponding formula in Table 8. The results are summarized in Table 16. In the neutral state, the skin temperature of the lower back was the highest ( $T_a = 27.6\text{ }^\circ\text{C}$ ,  $T_{sk} = 34.7\text{ }^\circ\text{C}$ ). By comparing the neutral skin temperatures of elderly (Xiong et al., 2019) and young (Atmaca & Yigit, 2006; L. Wang et al., 2019) people in other studies (Table 16), it can be found that the skin temperature of the distal regions (head, hand, and foot) of elderly people was lower than that of young people. This is consistent with the observation that elderly individuals exhibit decreased skin blood flow to their extremities (Guergova & Dufour, 2011). When the  $T_a$  rose, the skin temperature of the palm increased rapidly and reached the highest value ( $T_a = 32\text{ }^\circ\text{C}$ ,  $T_{sk} = 36.1\text{ }^\circ\text{C}$ ). This suggests that the limbs and extremities heat faster than other body parts and play a role in heat dissipation under warm conditions.

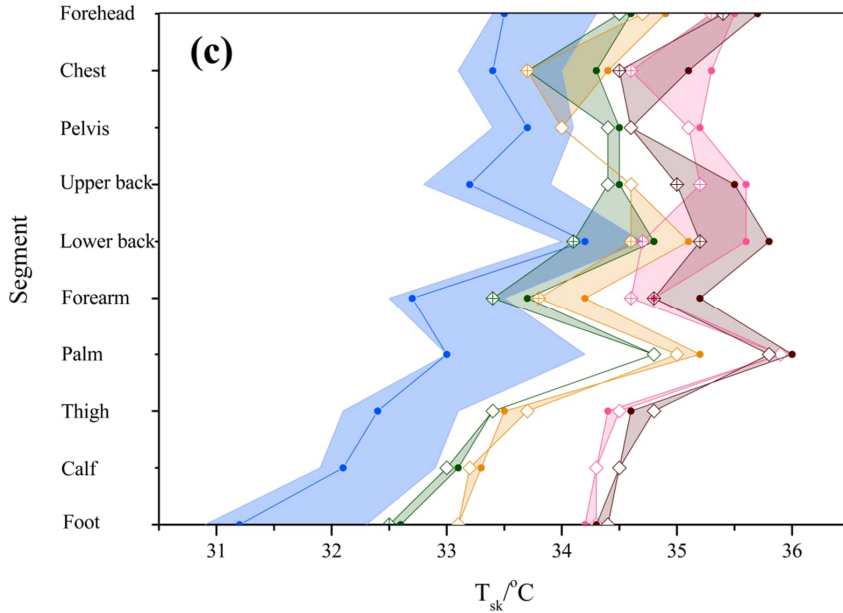
**Table 16.** Neutral skin temperature range of each body part.

Body part	Neutral skin temperature ( $^\circ\text{C}$ )			
	Elderly people		Young people	
	This study	Xiong et al.	Wang et al.	Atmaca et al.
Head	34.3	33.4	34.9	35.6
Chest	34.0	34.0	35.0	33.6
Pelvis	34.1	34.0	35.2	33.4
Upper back	33.9	33.8	34.2	33.2
Lower back	34.7	33.8	34.2	33.2
Forearm	33.5	32.7	32.0	–
Hand	34.2	32.3 (back)	34.0 (back)	35.2
Thigh	33.1	32.7	33.8	33.8
Calf	32.9	32.3	32.2	33.4
Foot	32.3	31.8	32.7	33.9

The changes in local skin temperature were analyzed using data from the last minute ( $t = 35\text{ min}$ ) of each phase, which represents a steady state. Data was analyzed using the paired t-test. The results are shown in Figure 25. The dots represent the skin temperature before using the device, the squares represent the skin temperature after using the device (a square containing  $\times$  inside indicates a significant difference), and the shaded area between them represents the change in

skin temperature (the blue area indicates the neutral range of skin temperature based on Table 16).





**Figure 25.** Local skin temperature before and after using local cooling devices: (a) table fan, (b) evaporative cooling device, and (c) air-cooled jacket.

For all devices, the local skin temperature of each part was within the neutral range at 26 °C, 40% RH. Combined with the measurement points of skin temperature in the elderly experiment, the body parts that were exposed to local cooling owing to the use of devices were defined as shown in Table 17.

**Table 17.** Body parts exposed to local cooling devices.

Device	Major exposed parts	Minor exposed parts	Unexposed parts
Table fan	Chest, forearm, and palm	Forehead and thigh	Pelvis, upper back, lower back, calf, and foot
Evaporative cooling device	Chest, forearm, and palm (including the wrist and finger, which contact with the palm)	Forehead and thigh	Pelvis, upper back, lower back, calf, and foot
Air-cooled jacket	Chest, upper back, lower back, and forearm	Forehead	Palm, pelvis, thigh, calf, and foot

\*Major exposed part: local body part with a significant decrease in skin temperature under all conditions.

\*Minor exposed part: local body part with a significant decrease in skin temperature under certain conditions.

\*Unexposed parts: local body parts with no significant decrease in skin temperature under any condition.

Because all body parts were in their neutral range at 26 °C, 40% RH, only the remaining four conditions were further examined. It could be found that both the

evaporative cooling device and air-cooled jacket showed better cooling in warm conditions than in slightly warm conditions, whereas the opposite was true for the table fan. Firstly, this may be related to the varying speed of the local cooling device under various conditions. All three devices utilize higher speeds in warm conditions than in slightly warm conditions. However, the table fan did not reduce the skin temperature more under warm conditions despite increasing the power, whereas the other two devices were able to reduce the skin temperature more effectively. This may be due to increased convective heat dissipation from the evaporative cooling device, which has cooler outlet air in a warmer environment, thereby decreasing the skin temperature. On the other hand, the outlet air of the air-cooled jacket had the same temperature as the background air, but the velocity was much higher near the skin. It mainly acted on the torso with a higher sweat rate (Inoue et al., 1991; Kenney & Munce, 2003), leading to higher convective and latent heat dissipation, which resulted in lower skin temperature.

After using the three devices, the skin temperature of the exposed body parts decreased significantly, bringing them closer to their neutral zones, whereas the skin temperature of the unexposed parts remained nearly constant, deviating more from their neutral values than the exposed parts. This indicates that the local cooling devices used in this study can only adjust the skin temperature of the exposed parts. The unexposed parts, including the lower back for the table fan and evaporative cooling device and the palm for the air-cooled jacket, had the highest skin temperature. For the three devices, the body part with the lowest skin temperature was not necessarily an exposed part, but mainly the lower body, including the foot and calf. This may be because staying in a sitting position for a long time reduces the skin temperature of the lower body (Garcia-Souto & Dabnichki, 2013; Huizenga et al., 2004; Xiong et al., 2016).

### 3.2.5 Changes of overall thermal sensation, air movement sensation, and device usage during local cooling phase

The device use rate ( $R_U$ ) and proportion of device adjustments ( $P_A$ ) during a certain time period were used to describe behavior during local cooling phase. The formulas for calculating  $R_U$  and  $P_A$  are:

$$= \frac{1 - \bar{A}_2}{\text{total}} \quad (7)$$

$$= \frac{1 - \bar{A}_2}{\text{total}} \quad (8)$$

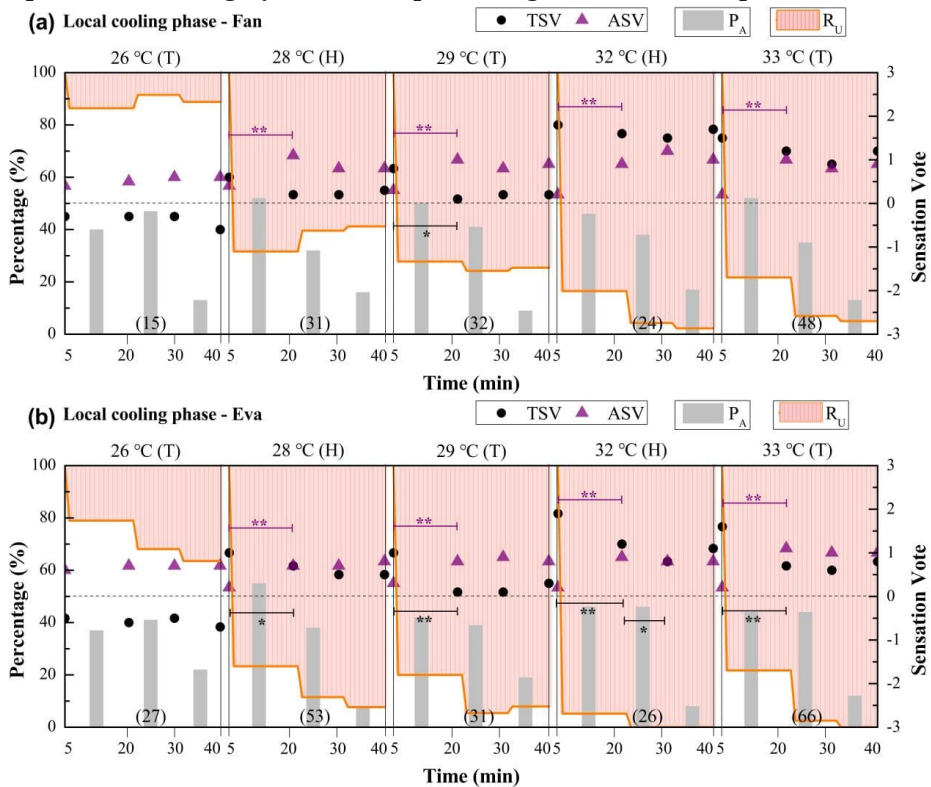
: Use rate of the device in a period,

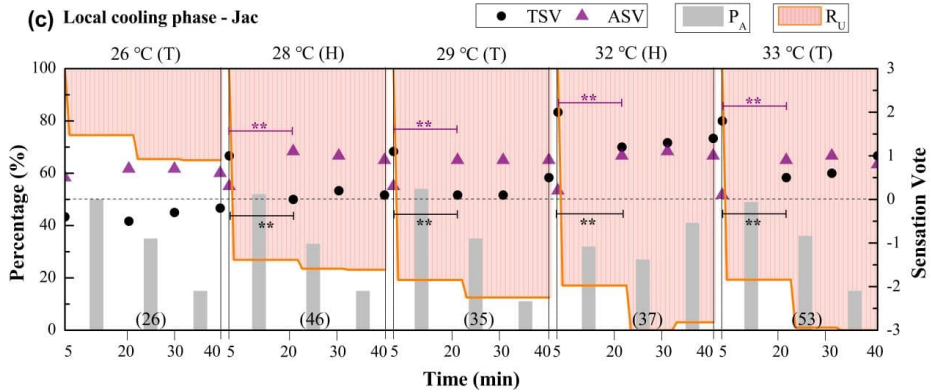
$1 - \bar{A}_2$ : Number of participants who use the device at time  $t_1 - t_2$ ,

total: Total number of participants in a specific test condition,

: Proportion of device adjustments in a period,  
 $n_{1-2}$ : Number of times the device was adjusted during  $t_1 - t_2$ ,  
 $n_{total}$ : Total number of adjustments in the specific test conditions,  
 $t_1 - t_2$ : Different time periods in local cooling phase, including T5–T20, T20–T30, and T30–T40 (The data at the 5th minute came from the end of the previous phase, and the 20th, 30th, and 40th minutes were the time points for filling out the questionnaire during local cooling phases).

Repeated measure ANOVA was used to explore the psychological dynamic change of TSV and ASV among data from T5, T20, T30, and T40. Results are shown in Figure 26 with the pink shaded regions representing the average  $R_U$  value of three time periods, and the gray columns representing  $P_A$  in three time periods.





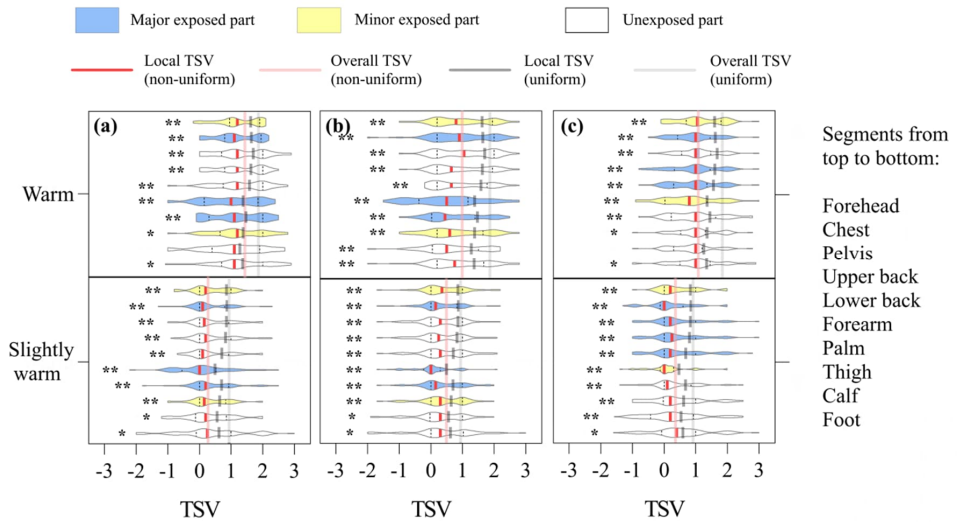
**Figure 26.** The dynamic process of local cooling devices usage phases (the numbers in parentheses at the bottom are the total times of adjustment of participants under each condition, (a) Fan = table fan, (b) Eva = evaporative cooling device, and (c) Jac = air-cooled jacket).

Significant differences ( $p < 0.01$ ) in TSV and ASV were observed only between T5 and T20, whereas when using the evaporative cooling device at 32 °C (H), significant differences in TSV were observed between T20 and T30 ( $p < 0.05$ ). This demonstrates that thermal and air movement sensation varied markedly within the first 15 min and subsequently stabilized.

$R_U$  changed the most between T5 and T20 for the three devices under each condition, remained similar for T20–T30 and T30–T40, and changed greatly in the first 15 min and remained nearly unchanged thereafter.  $P_A$  of the three devices decreased with time.  $P_A$  for T0–T15, T15–T25, and T25–T35 was approximately 50%, 40%, and 10%, respectively. Most of the adjustments made by the elderly occurred within the first 25 min, after which almost no adjustments were made.

### 3.2.6 Variation of local thermal sensation before and after use of local cooling devices

Changes in local thermal sensation were analyzed using data from the last questionnaire of each phase. The results are shown in Figure 27. The gray line represents the TSV before using the device, and the red line represents the TSV after using the device. The blue area are the major exposed parts, the yellow area are the minor exposed parts, and the white area are the unexposed parts of the three local cooling devices. From top to bottom, the local parts are forehead, chest, pelvis, upper back, lower back, forearm, palm, thigh, calf, and foot.



**Figure 27.** Local thermal sensation before and after using local cooling devices: (a) table fan, (b) evaporative cooling device, and (c) air-cooled jacket.

The effect of the devices on thermal sensation was consistent with that on skin temperature under different conditions. The evaporative cooling device and air-cooled jacket reduced the thermal sensation more in warm conditions, whereas the table fan reduced the thermal sensation more in slightly warm conditions. The TSV of the upper body, which includes the major exposed parts, varied more than that of the lower body. Some unexposed areas also experienced a significant change in thermal sensation. For example, with the set airflow pattern, the table fan and evaporative cooling devices mainly influenced the chest, but the TSV of the pelvis and back changed similarly. The inability of the elderly participants to correctly recognize the thermal sensations of all local body parts may be one of the causes of this unexpected result. However, some comparable experiments conducted on young participants reported similar results (He et al., 2022; Yang et al., 2020; Y. Zhang & Zhao, 2007). Consequently, another possible explanation is that the questionnaires were filled out during the participants' steady state (the final 5 min of each phase), implying that the time interval between the inquiries about local thermal sensation was long, and thus, the local thermal sensation may have been affected by the overall thermal sensation. The overall TSV was consistent with or even slightly higher than the parts with the highest TSV. This result is consistent with the findings of previous studies (Yao et al., 2007; H. Zhang et al., 2010), which concluded that the perception of overall discomfort depends on the local body part that experiences the most intense discomfort. In the present study, the overall TSV may be the collective effect of multiple parts with the highest TSV.

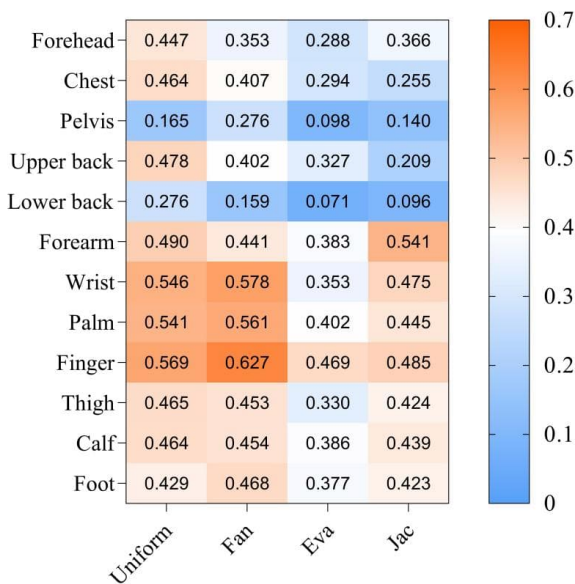
### 3.3 The relationship between skin temperature, thermal sensation, and device usage behavior among elderly people

In this subsection, the relationship between skin temperature, thermal sensation, and device usage behavior of elderly people not only in steady state, but also in transient state is explored. Furthermore, the focus is not only on the whole set of elderly participants but also individuals.

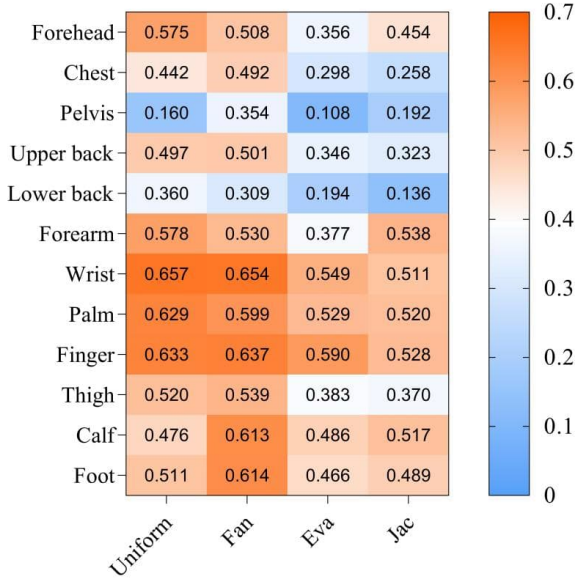
#### 3.3.1 Correlation between skin temperature and thermal sensation

The correlation between the skin temperature and TSV at the end of each phase was analyzed. Figure 28 shows the results, where the value in the cell represents the Pearson correlation coefficient. The finger and wrist skin temperatures correspond to the TSV of the palm.

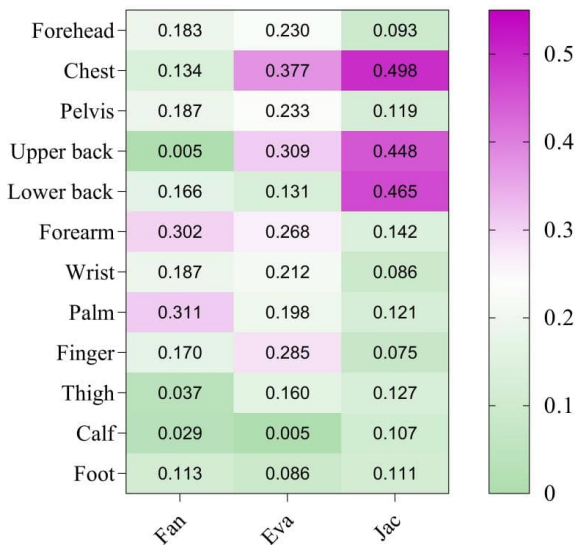
(a) Correlation between local  $T_{sk}$  and local TSV



**(b)** Correlation between local  $T_{sk}$  and overall TSV



**(c)** Correlation between the change of local  $T_{sk}$  and the change of overall TSV



**Figure 28.** Correlation between (a) local skin temperature  $T_{sk}$  and local thermal sensation vote (TSV), (b) local  $T_{sk}$  and overall TSV, and (c) the change in local  $T_{sk}$  local and the change in overall TSV. (Uniform, no cooling device used; Fan, table fan; Eva, evaporative cooling device; Jac, air-cooled jacket.)

Figure 28(a) illustrates the relationship between the local skin temperature and local TSV. All parts except the pelvis and lower back showed a strong correlation between the skin temperature and TSV in a uniform environment. In a nonuniform environment (using a table fan, evaporative cooler, or air-cooled jacket), only the skin temperatures of the limbs and extremities correlated more strongly with their TSV. Figure 28(b) shows the correlation between the local skin temperature and overall TSV. In all cases, the forehead, limbs, and extremities exhibited stronger correlations than the torso. Figure 28(c) shows the correlation between changes in the local skin temperature and changes in the overall TSV. The forearm and palm, the parts with the greatest decrease in skin temperature after using the table fan, had a higher correlation with the overall TSV change. The use of an evaporative cooling device or air-cooled jacket yielded the same results, indicating that the exposed parts with a greater reduction in skin temperature were more strongly correlated with the overall TSV change. This suggests that these major exposed parts were responsible for variations in the overall thermal sensation.

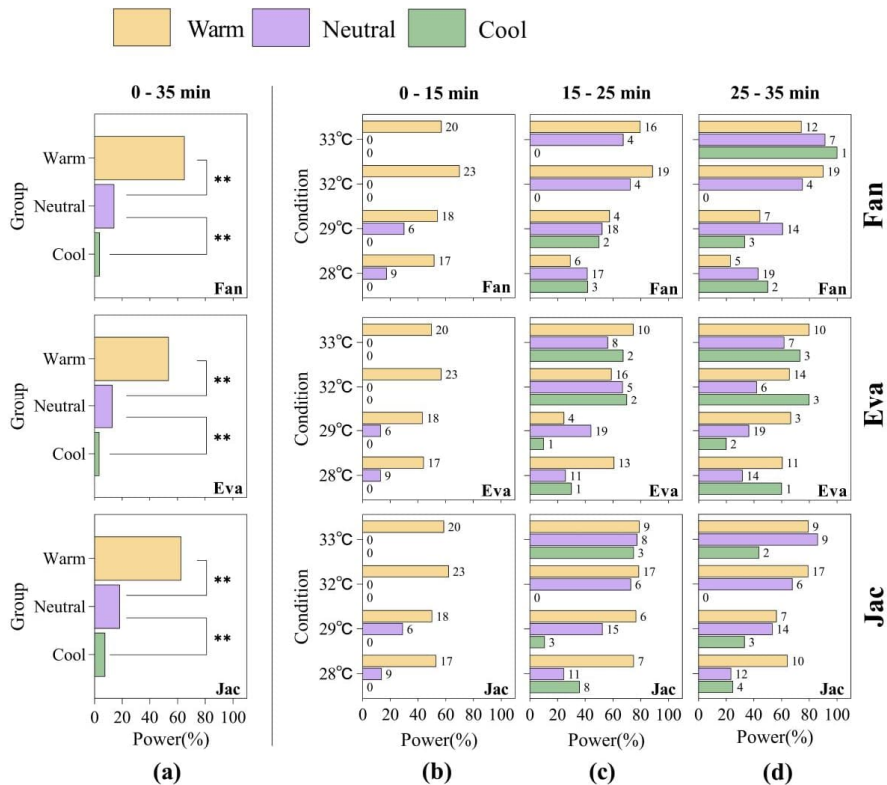
The pelvis and lower back showed a low correlation with thermal sensation in both uniform and non-uniform environment. It might be because they belong to the core body area, and thus their skin temperatures may remain stable in changing environments. The small linear regression coefficient between their local skin temperature and  $T_a$  (Table 8) supports this hypothesis. When significant changes occurred in overall thermal sensation and local thermal sensation of pelvis (Figure 27), skin temperature of pelvis did not undergo substantial alterations (Figure 25). Consequently, the skin temperature of the pelvis, in comparison to other parts, fails to reflect thermal sensation. After using local cooling devices, the skin temperatures of the limbs and extremities were strongly correlated not only with their own local TSV but also with the overall TSV, with the highest correlation coefficient found for the finger. This may be because the limbs and extremities, particularly the upper limbs, are exposed to the environment, making their skin temperatures sensitive to  $T_a$  (Table 8). In elevated  $T_a$ , the human body's extra heat needed to be dissipated through these parts (Romanovsky, 2014), which served as radiators, by vasodilation. The finger, which contains a large number of arteriovenous anastomoses (AVAs), reflects the thermal state of the human body (Karakı et al., 2013). Although the number of AVAs is reduced in elderly people (Van Someren, 2007), the present study revealed that the correlation of  $T_{sk}$  of the finger with thermal sensation was still higher than that of other parts of the body.

Contrasting the correlation coefficients of skin temperature for each body part with overall thermal sensation and the weights of local thermal sensation on overall thermal sensation, it is evident that the head and hand possess higher coefficients and greater weights compared to other parts. This suggests that using local cooling devices in a warm environment, the thermal sensation of the head and hands will

more significantly influence overall thermal sensation, and their skin temperatures can be used as indicators for assessing overall thermal sensation.

### 3.3.2 Thermal sensation and the control of local cooling devices

The participants were categorized into three groups based on their TSV—neutral ( $-0.5 \leq \text{TSV} \leq 0.5$ ), warm ( $\text{TSV} > 0.5$ ), and cool ( $\text{TSV} < -0.5$ )—and compared based on it with the average power usage of the devices over a period of time after voting. Figure 29 shows the results. Yellow, purple, and green represent the warm, neutral, and cool groups, respectively. The lengths of the bars indicate the average power usage, and the numbers at the top of the bars refer to the number of individuals in each group. Figure 29(a) uses TSV data from the steady-state rest phases across all conditions to categorize the participants, and it combines the average power usage over the entire local cooling phase. Figure 29(b), (c), and (d) present more detailed results for different time periods across the four conditions. These figures use TSV data from the rest phase, the 15<sup>th</sup> minute of the local cooling phase, and the 25<sup>th</sup> minute of the local cooling phase to categorize the participants and correlate these with the average device power usage during subsequent periods: the first 15 minutes, 15–25 minutes, and 25–35 minutes of the local cooling phase, respectively.



**Figure 29.** Average usage power of devices by different thermal sensation groups.

Figure 29(a) denotes that a higher TSV in the rest phase was correlated with greater average power usage during the local cooling phase. There were significant differences in the average power usage between the warm, neutral, and cool groups. This implies a certain consistency between the thermal sensations of older adults and their device usage when air temperature variations are considered. Figure 29(b) shows that a higher TSV in the rest phase led to a higher average power usage within the first 15 minutes of using any local cooling device under all conditions. This suggests that device usage during the first 15 minutes was consistent with the initial thermal sensation.

Figure 29(c) displays the results of the grouping based on the 15<sup>th</sup>-minute TSV. Compared to the first 15 minutes, the number of participants in the warm group significantly declined, whereas the numbers in the neutral and cool groups increased. Additionally, the warm group's device power was higher in this period than in the previous one, indicating that those feeling warm attempted to use higher power to alleviate thermal discomfort. Meanwhile, the neutral and cool groups' device power in this period was similar to (or even lower than) that of the warm group in the previous period, suggesting that prior local cooling had already brought these participants to a neutral or cool state. Thus, they did not increase the device power. This phenomenon also reflects the consistency between thermal sensation and device usage. Overall, the higher the TSV after using the local cooling device for 15 minutes, the higher the average power usage in the following 10 minutes.

Figure 29(d) outlines the results of the grouping based on the 25<sup>th</sup>-minute TSV. Compared with the previous 10 minutes, the number of participants in the warm group fell slightly, whereas the numbers in the neutral and cool groups rose slightly. During this period, the device power usage for each group remained almost the same as that of the prior period. Additionally, more special cases appeared, reflecting increasing individual differences in thermal comfort needs over time. Although the participants in the warm group felt warm, not everyone in this group chose to use 100% of the device power in the final period. This could be due to individual differences as the local cooling devices provided in the current study were convective and there may have been varying preferences for airflow.

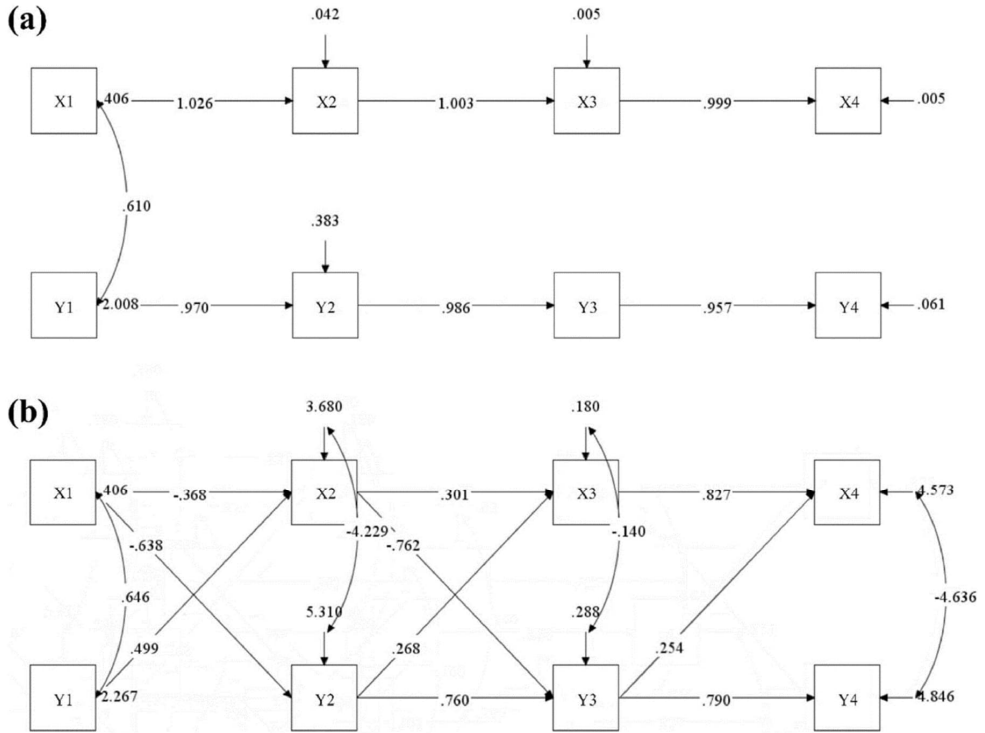
To summarize, because the participants stayed in an environment beyond their acceptable temperature range (Section 3.1.2) for 40 minutes, their TSVs were more similar at the beginning of the local cooling phase, resulting in the strongest consistency between the device power usage and TSV. As the participants used cooling devices to reduce the TSV over time, more inter-individual differences (e.g., thermal preference, adaptation ability, etc.) weakened this consistency.

### 3.3.3 Mean skin temperature and the control of local cooling devices

In this study, a cross-lagged panel model was employed to further investigate the causal relationship over time between mean skin temperature (variable X) and device usage (variable Y). Here, device usage is denoted by the measure  $T_{eq}$  (Table 15). As the  $T_{eq}$  of the three devices at different speeds under the 28 °C and 32 °C conditions were not measured, the necessary data was supplemented using interpolation.

For the analysis, the data from the three devices at 28 °C, 29 °C, 32 °C, and 33 °C (excluding the 26 °C condition, where almost no device usage occurred) was utilized. As most adjustments to the devices happened in the first 15 minutes, to avoid the impact of different lengths of time, four equidistant time points (T1–T4) during the first 15 minutes of the local cooling phase were selected to examine the relationship between the mean skin temperature (X1–X4) and  $T_{eq}$  (Y1–Y4) while using the cooling devices. The mean skin temperature (X1) at the end of the rest phase and the ambient temperature (Y1) served as the values at time T1. The data for T2–T4 were derived from the local cooling phase, with the skin and  $T_{eq}$  assigned at intervals of  $t$  minutes from the start of the local cooling phase for each time point ( $t=1, 2, 3, 4, \text{ and } 5$ ).

Figure 30 illustrates the autoregressive paths for variable X ( $X_i \rightarrow X_{i+1}, i=1,2,3$ ), the autoregressive paths for variable Y ( $Y_i \rightarrow Y_{i+1}, i=1,2,3$ ), the correlation paths between variables X and Y ( $X_i \rightarrow Y_i, i=1,2,3$ ), the cross-lagged effects of variable X on variable Y ( $X_i \rightarrow Y_{i+1}, i=1,2,3$ ), and the cross-lagged effects of variable Y on variable X ( $Y_i \rightarrow X_{i+1}, i=1,2,3$ ). The presence of paths between the variables indicates significant correlations, with path values representing the correlation coefficients. The model with 1-minute intervals, as shown in Figure 30(a), only revealed autocorrelations within the variables, with no significant correlations or cross-lagged effects observed between variables X and Y. This may be due to the minimal variation in the variables at their respective periods when using a 1-minute interval.



**Figure 30.** Cross-lagged model for (a) t=1 min, and (b) t=5 min.

Figure 30(b) presents the model with a 5-minute interval, showing increasing autocorrelation coefficients for both X and Y, reflecting that both skin temperature and  $T_{eq}$  (device usage) tended to stabilize over time, which is consistent with previous findings. At time T1, X1 was positively correlated with Y1 because local cooling devices had not yet been used. Y1 denotes the ambient temperature, suggesting that higher ambient temperatures correspond to higher skin temperatures. The X and Y residuals were negatively correlated at T2, T3, and T4. It was posited that higher skin temperatures, associated with higher thermal sensations, would lead to the selection of a higher device power equal to a lower  $T_{eq}$ . This hypothesis was supported by the cross-lagged paths between variables X and Y: The average skin temperature at T1 (X1) was negatively correlated with  $T_{eq}$  at T2 (Y2), and X2 was negatively correlated with Y3, implying that higher skin temperatures 5 minutes prior led to increased device power usage, resulting in a lower  $T_{eq}$ . Conversely,  $T_{eq}$  at T1 (Y1) was positively correlated with the mean skin temperature at T2 (X2), Y2 with X3, and Y3 with X4, suggesting that higher  $T_{eq}$  occurring 5 minutes prior led to higher skin temperatures at the current moment.

To evaluate the model, the chi-square/df ratio ( $\chi^2/df$ ) was used as a criterion for assessing model fit, with an  $\chi^2/df$  value below 5 indicating a good fit (Hu & Bentler, 1999; Kim et al., 2018). The comparative fit index (CFI) and Tucker–Lewis index

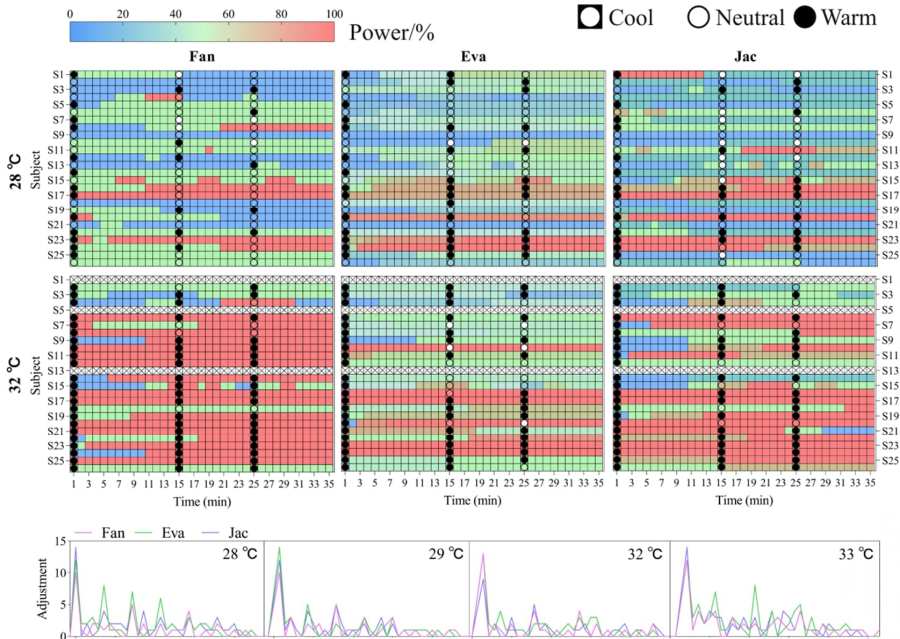
(TLI) are also commonly employed to assess model fit, with values above 0.95 implying a good fit (Hu & Bentler, 1999; Kim et al., 2018). Additionally, the root mean square error of approximation (RMSEA) is a widely used metric for model evaluation, where an RMSEA of 0.06 or lower suggests a good fit. An RMSEA value of 0.1 denotes a mediocre fit, and an RMSEA greater than 0.1 indicates that the model requires adjustment (Browne & Cudeck, 1992). The models established at the 1-, 2-, 3-, 4, and 5-minute intervals are presented in Table 18, which shows that only the model with a 5-minute interval met all evaluation criteria. Therefore, we can infer that the current device usage behavior of older adults is better related to their skin temperature 5 minutes prior.

**Table 18.** Model fit indices for the cross-lagged analyses.

Model	$\chi^2/df$	AIC	CFI	TLI	RMSEA
$t=1\text{min}$	6.121	971.981	0.965	0.935	0.138
$t=2\text{min}$	6.539	1173.186	0.969	0.944	0.143
$t=3\text{min}$	4.978	1438.319	0.973	0.950	0.121
$t=4\text{min}$	4.141	1548.191	0.982	0.967	0.108
$t=5\text{min}$	3.627	1429.931	0.985	0.972	0.099

### 3.3.4 Individual thermal preferences and the control of local cooling devices

The above analysis suggests that, on average, the participants' psychological thermal sensations aligned with their behavior, although there were individual differences. For this section, the 28 °C and 32 °C conditions were used as examples, demonstrating each individual's control over the device as displayed in the figures. Figure 31(a) depicts a heat map representing the power usage of each device per minute by all participants (subject 1–26 on the y-axis) throughout the entire local cooling phase (0–35 minutes on the x-axis), with darker colors indicating greater power usage. Fig. 9(a) also illustrates each participant's TSV group; a white circle denotes warm ( $TSV > 0.5$ ), an empty circle implies neutrality ( $-0.5 \leq TSV \leq 0.5$ ), and a black circle refers to cool ( $TSV < -0.5$ ). Figure 31(b) shows the number of adjustments made by the participants using different devices across the four conditions over time.



**Figure 31.** Individual control of the three devices under the 28 °C and 32 °C conditions with their respective thermal sensation group.

As stated in Section 3.1.1, inconsistencies between the TSV and power usage for the time range between 15–35 minutes were observed. Figure 31 (a) reveals why power usage in the cool group was higher than that in the neutral and warm groups. Firstly, some individuals, such as S7 and S10, did not reduce their power usage despite their TSV being lower than  $-0.5$ , and in some cases, they even increased it. Secondly, other individuals, such as S3 and S19, did not increase their power usage despite their TSV being higher than  $0.5$ , and some even reduced it. Thirdly, individuals S5 and S18 maintained a neutral thermal sensation, even with low power usage. Moreover, most individuals in the hot group maintained their current power settings and did not increase their power usage in response to feeling warmer.

Because TSV data were only available at three time points, in the previous analyses, the focus is on the relationship between TSV and average power usage. However, the participants not only adjusted the devices when voting but also likely made adjustments throughout the entire local cooling phase. Although individual adjustment patterns are challenging to summarize, Figure 31(b) shows that most adjustments occurred within the first 15 minutes, indicating that most participants initially actively attempted to regulate their devices to alleviate thermal discomfort. The adjustment frequency varied among the devices. The evaporative cooling device was adjusted most frequently, followed by the air-cooled jacket, with the fan

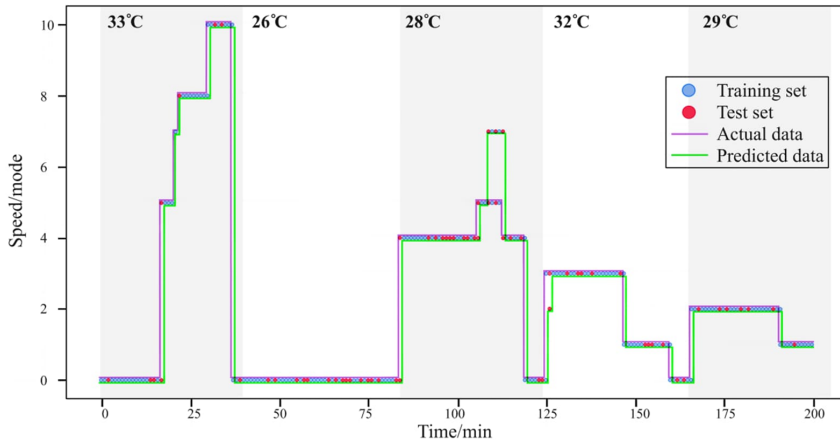
adjusted the least. This variation is likely related to the different modes available for each device as the evaporative cooling device has ten speeds, the air-cooled jacket has four, and the fan has two.

### **3.3.5 Predicting individual control of local cooling devices**

Due to the variations in control behavior among individuals using different devices, considering that the device usage behavior changing over time and owing to other influencing factors, an LSTM model was deemed to be suitable for exploring this behavior from the relevant data. The use of an LSTM model to predict individuals' dynamic device usage was explored and the impact of different input features on the prediction was evaluated.

Among all the participants involved in the five test conditions, nine who made multiple adjustments to their devices were selected for further exploration. A model for each participant's control behavior for each device was built. The main framework of the model includes (1) input data, which are determined by the number of factors that affect the device; (2) the LSTM layer, embedded to memorize and extract the information contained in the input data; (3) the ADAM optimizer, used to update the weights and biases; and (4) after the termination criteria are met, a fully connected layer that provides the final output.

The skin temperatures of the head and wrist—which showed the strongest correlation with thermal sensation—and the speed of the device were selected as the input features (all from the previous 5 minutes). The speed of the device in the subsequent minute was the output. The cross-entropy was employed as the loss function and classification accuracy to evaluate the model's performance. Figure 32 illustrates the results for Participant 3 using the evaporative cooling device when the input features included the forehead and wrist skin temperatures. Table 19 displays the prediction outcomes of the model when different input features were used (the average accuracy of the three devices). The accuracy was approximately 50% when only one skin temperature input was utilized, with the wrist skin temperature providing slightly higher accuracy than the forehead skin temperature. When both skin temperatures were used as inputs, the accuracy improved by about 65%. Using only the speed of the device as input yielded an accuracy of approximately 85%. The highest accuracy (around 90%) was achieved when all three variables were inputted together.



**Figure 32.** Results of training and Participant 3’s usage behavior when using the evaporative cooling device.

**Table 19.** Prediction accuracy of the model with different input features.

Input features	Test accuracy								
	P3	P6	P7	P9	P11	P12	P14	P17	P20
$T_{\text{forehead}}$	45%	47%	50%	72%	13%	45%	52%	40%	52%
$T_{\text{wrist}}$	50%	38%	70%	70%	30%	68%	60%	55%	50%
$T_{\text{forehead}}$ and $T_{\text{wrist}}$	67%	72%	68%	83%	48%	50%	75%	77%	65%
Speed	88%	85%	88%	83%	85%	93%	88%	93%	83%
$T_{\text{forehead}}$ , $T_{\text{wrist}}$ , and speed	89%	87%	82%	93%	92%	95%	88%	90%	95%

P: participant;  $T_{\text{forehead}}$ : skin temperature of the forehead;  $T_{\text{wrist}}$ : skin temperature of the wrist.

### 3.4 A novel PCS and its effectiveness under warm conditions

In this subsection the directions for improving local cooling devices based on experiments with elderly people and the effects of the new PCS in hot environments are presented.

#### 3.4.1 Weights of local thermal sensation on overall thermal sensation

Based on the analysis of the local thermal sensation on overall thermal sensation, the human body could be divided into four areas: head, torso, upper limbs, and lower limbs. The results of their respective influence weights on the overall thermal

sensation are shown in Table 20, In a steady uniform thermal environment, the torso, particularly the chest and upper back, had the greatest weight. This emphasizes the primary task of cooling the torso region. The second-highest weighted area is the lower limbs, followed by the upper limbs and head. It seems that larger body areas had greater weight.

**Table 20.** Weight of local thermal sensation on overall thermal sensation after using three local cooling devices.

Local thermal sensation weights of four areas				
Area	Uniform	Fan	Eva	Jac
Head	0.12	0.16	0.19	0.28
Torso	0.48	0.37	0.46	0.38
Upper limbs	0.17	0.25	0.28	0.19
Lower limbs	0.24	0.23	0.06	0.14

After using the table fan, there was a minimal decrease in skin temperature of the torso region, resulting in a mere 0.3 reduction in the participants' overall TSV. This indicates that the table fan did not effectively dissipate the heat accumulated in the torso region. Consequently, the skin temperatures of the limbs (arm and leg) and extremities (head, hand, and foot) remained high to enhance heat dissipation. Meanwhile, these areas exhibited higher thermal sensations, which may contribute to increasing their weights on overall thermal sensation.

After using the evaporative cooling device, a substantial decrease in skin temperature was observed in the chest and forearm. The overall TSV decreased by 0.9, shifting the participants' thermal sensation from "hot" to "warm." The weight of the torso and upper limbs was 0.74, reflecting the significant reduction in skin temperature in these exposed areas greatly influencing overall thermal sensation.

After using the air-cooled jacket, the reduction in skin temperature of the torso region surpassed that of the table fan and evaporative cooling device, especially in the chest and lower back. The overall TSV decreased by 0.6, transitioning the participants' thermal sensation from "hot" to "warm." Unlike the other two devices, after using the air-cooled jacket, the TSV of the head was greater than the torso, indicating that the head is the warmest part of the body. This may be attributed to the fact that the airflow from the table fan and evaporative cooling device affected the head, resulting in lower head skin temperature and thermal sensation when using these two devices compared to the air-cooled jacket.

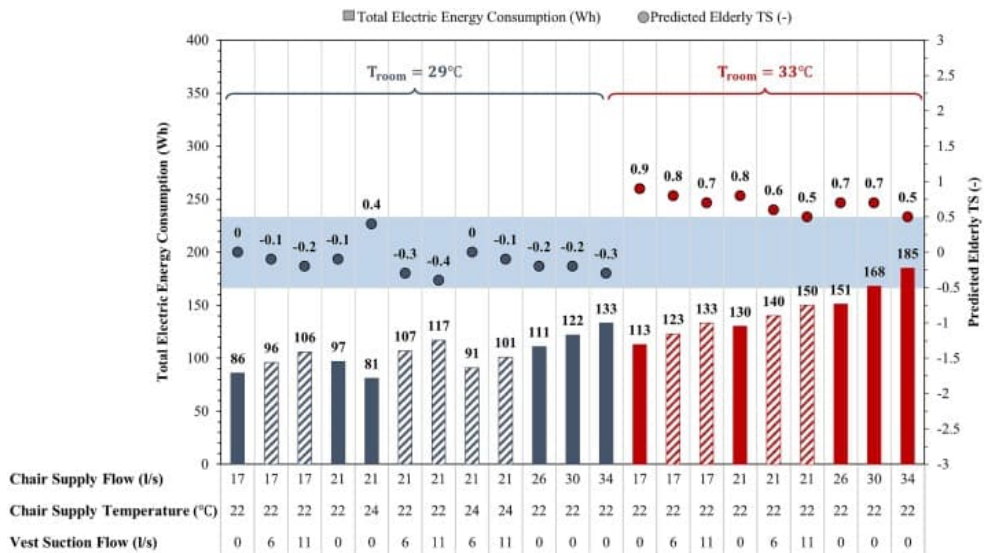
In summary, cooling the torso of elderly people is essential in the hot environment. A low-speed room-temperature airflow table fan is not effective in enhancing torso heat dissipation. Instead, evaporative cooling devices with low-speed and low-temperature airflow or air-cooled jacket with high-speed room-temperature airflow could be considered. While maintaining the original airflow

parameters, the improvement suggestion for the evaporative cooling device is to increase the exposed area, directing a larger airflow towards the head while allowing the descending cold air to affect the thighs. As for the air-cooled jacket, the recommendation is to enhance the airflow near the head, such as by adding an additional fan unit on the chest area of the garment.

### 3.4.2 The effectiveness of the combination of cooling chair system and ventilated jacket

The novel PCS includes an evaporative cooling chair and a ventilated jacket. The cooling chair has air outlets at the armrests that deliver air to both the upper and lower body, creating a microenvironment that covers almost the entire body. The exhaust air of the ventilated jacket is affected by both the microenvironment and the background environment.

The effect of using only the cooling chair and the effect of using the ventilated jacket in combination with the cooling chair are shown in Figure 33. Figure 33 also shows the energy savings achieved through employing the ventilated jacket with the chair PCS compared to the single cooling chair.



**Figure 33.** Cooling chair energy consumption, with and without employing the ventilated jacket, under different configurations and the corresponding elderly thermal sensation state.

At 33 °C, running the chair PCS at a flow rate of 17 l/s and supply temperature of 22 °C while simultaneously activating the jacket at a flow of 6 l/s resulted in a similar TS ( $0.7 \leq TS \leq 0.9$ ) to operating the chair PCS alone at a supply rate of 21 l/s but with a 6 % reduction in energy consumption. Similarly, when the chair PCS

operated at a flow rate of 17 l/s with the jacket running at 11 l/s, the TS ranged from 0.6 to 0.8, similar to the TS achieved when the chair PCS was used alone at a supply rate of 21 l/s, yet with a 12 % decrease in energy consumption. For cases where chair supply flow was 21 l/s and jacket flows were 6 l/s and 11 l/s, respectively, it was determined that the stand-alone chair system should be operated at flow rates ranging between 30 l/s and 34 l/s, to correspond to the similar TS ( $0.4 \leq TS \leq 0.7$ ). The integration of the jacket in these scenarios led to more than 19 % energy savings in comparison to the stand-alone system. It should be noted that the average air velocity near the head, under conditions of 30 and 34 l/s, surpasses the 0.4 m/s threshold which might cause draft discomfort.

At an ambient temperature of 29 °C, operating the chair PCS at 17 l/s at 22 °C and activating the jacket at 6 l/s yields a similar TS ( $0.0 \leq TS \leq -0.2$ ) as using the chair PCS alone at 21 l/s. Likewise, using the jacket at 11 l/s in conjunction with the chair PCS is comparable ( $-0.1 \leq TS \leq -0.3$ ) to operating the chair PCS alone at 26 l/s. In these cases, energy consumption decreased by 1 % and 4 %, respectively. Operating the chair PCS at 21 l/s achieved a comparable TS ( $TS \leq -0.3$ ) to running the chair PCS alone at about 34 l/s, leading to 19 % energy savings, but resulted in cooler TS than thermal neutrality, making jacket integration unadvisable in this situation when the supply is at 22 °C. At 24 °C supply temperature, the integrated mode of the system with 11 l/s suction flow resulted in similar TS to the standalone mode at 21 l/s / 22 °C, though with a 4 % increase in needed energy. When the suction flow was 6 l/s, the integrated mode of the system resulted in neutral sensation, similar to the standalone mode at 17 l/s / 22 °C, but it used 15 % more energy.

## 4 Discussion

In this thesis changes in physiological and psychological parameters of the elderly in warm environments were investigated. The impact of three different local cooling devices on the enhancement of thermal comfort was also assessed. Then, a novel individual thermal comfort system for the elderly was proposed. Climate chamber experiments with elderly participants and a thermal manikin to analyze the thermal response and the effectiveness of cooling devices from both subjective and objective perspectives were conducted. At the same time, the performance of the new personal comfort system was assessed in combination with CFD, and its effect in a warm environment was evaluated.

This study provides a reference for the setting of indoor environmental parameters for the elderly in the future and strategies for the control system of future smart homes. In addition to contributing to the design of the entire indoor environment, this study can provide more opinions on the design of individual microenvironments. Since individuals have different objective physiology and subjective feelings, local cooling devices, or PCS, that can provide individual control and create individual microenvironments can better meet the needs of different individuals. This study proposes some directions for the improvement of devices and provides a new individual thermal comfort system that can effectively create a microenvironment that keeps the elderly comfortable. It also contributes to the automatic control strategy of PCS.

### 4.1 Practical implications

Maivel et al. (Maivel et al., 2015) conducted a field study in 100 Estonian apartments to investigate the influence of ventilation, building orientation, and window size on recorded overheating in Northern European countries, which have cold winters and relatively warm summers. It was demonstrated that modern buildings were routinely overheated in the current climate of northern European countries in the absence of any passive solar protection solutions.

The national Finnish building codes and legislations requires that in the design phase, the maximum allowed design indoor air temperature is 27 °C outside the heating season; and in the occupied apartments, the upper limit for the indoor air

temperature of 32 °C (30 °C for vulnerable people), is used concerning the health and well-being of occupants in all the living spaces.

The thermal regulation and perception systems of older adults are different from those of younger ones due to aging, so the current building codes may not be applicable to the elderly. The results of this study (**Publication 1**) shows that the neutral thermal temperature of the Nordic elderly (wearing standard summer clothing around 0.5 clo) is about 26 °C, the upper limit of 80% acceptable is 28 °C, and the thermal sensation change rate is 0.324/°C. By comparing other elderly people experiments (Jiao et al., 2020; Kainaga et al., 2022; Schellen et al., 2010; Xiong et al., 2019) and young people experiments (Hwang & Chen, 2010; Liu et al., 2011; C. Peng, 2010; Q. Wu et al., 2020), it can be found that the acceptable temperature range of elderly people is narrower than that of young people, and the thermal sensitivity is lower. It is worth noting that the results of this study are only used to guide the creation of a "comfortable" thermal environment, not a "non-health-threatening" thermal environment. As nobody knows healthy limit, and it could be different in individuals, this comfort conditions could be considering one threshold value. Although these results cannot provide a clear reference for the elderly people upper limit temperature for residential building codes, they can provide a reference for providing a comfortable temperature for elderly homes.

On the other hand, most studies based on young populations have found that females are more critical of warm environments, with lower levels of comfort and a greater likelihood of expressing dissatisfaction (Ciuha & Mekjavic, 2016; Karjalainen, 2007; S. Zhang & Zhu, 2022). In contrast, in this study (**Publication 3**) it was found that older females had slightly higher acceptance and heat tolerance in warm environments than males, which is consistent with the findings of Jian et al. (Jian et al., 2022). This result may suggest that there is no need to develop gender-specific thermal environment standards for the elderly population. Other researchers (Karjalainen, 2007) have suggested that tolerance to indoor thermal environments may be influenced more by historical thermal experiences and cultural backgrounds than by physiological factors such as age and gender, which may explain the differences observed in the current study.

With low thermal sensitivity and a narrow thermal acceptance range, the elderly may experience rapid thermal unacceptability when their heat stress exceeds a certain threshold, which motivates them to use cooling devices. Jian et al. (Jian et al., 2022) confirm this hypothesis. They explored the relationship between air conditioner switch-on and elderly occupants' thermal tolerance and found that thermal unacceptability increased dramatically when indoor  $T_a$  reached 28.5 °C, a temperature a little higher than the upper-limit of temperature for 80% thermal acceptability. However, the occupants' thermal unacceptability did not necessarily lead immediately to air conditioner switch-on. According to the fan-use model obtained by He et al. (He et al., 2019) after analysing 54 studies, usage exceeded 50%

when the indoor  $T_a$  was 28.9 °C. Wu et al. (Y. Wu et al., 2019) discovered in a nursing home that fan usage of the elderly increased dramatically when the indoor  $T_a$  exceeded 29 °C, and air conditioning usage increased when the  $T_a$  exceeded 32.5 °C. The 50% utilization rate  $T_a$  in these studies were higher than the threshold  $T_a$  of 28.5 °C.

This study's upper limit of 80% acceptable temperature was 28 °C, and hence this threshold (28.5 °C) was also deemed appropriate for this study. In contrast, the 50% utilization rate  $T_a$  for three local cooling devices in this study was lower than 28.5 °C, which reflects that the elderly actively interact with devices to maintain thermal comfort even before finding the thermal environment unacceptable. Considering that the three convective local cooling devices in this study can significantly reduce thermal sensation in 28 °C and 29 °C conditions, and restore elderly people to a neutral thermal sensation; while in 32 °C and 33 °C conditions, it is almost impossible for the elderly to return to a neutral state, it can be concluded that these devices have a large potential to assist the elderly in maintaining thermal comfort during the transition phase from 28.5 °C to 32.5 °C. This result demonstrates the applicable temperature range of these convection-type local cooling devices, and also serves as a reference for the future development of automatic control strategies for air-conditioning-PCS linkage, making contributions to smart home systems.

The weights of local thermal sensation on overall thermal sensation were also analyzed in the thesis (**Publication 2**). Compared with the situation without local cooling devices, the weights of the head and upper limbs increased, and those of the torso and lower limbs decreased after using local cooling devices. In all cases, the torso had the greatest weight, whereas the lower limbs had the smallest weight (the head, with only one part, was not compared). This may be because the human torso contains the most vital organs and is the heat-producing center of the body. The torso accounts for approximately 30% of the body's total surface area (Tikusis et al., 2001). Thermal signals from this area serve as important auxiliary feedback signals in the control of autonomic thermoeffectors, which influence thermal sensation in the steady state of the human body (Romanovsky, 2014). In contrast, the lower limbs are sufficiently far from the core region (Park et al., 2011) such that the lower body contributes less to the overall thermal sensation. Although the surface area of the face accounts for approximately 4% of the total surface area, it contributes significantly to the total skin signal driving certain thermoeffectors (Nadel et al., 1973; Stevens & Choo, 1998), making the head a critical section.

Although it was found in this study that the change in overall thermal sensation was most correlated with the change in skin temperature in the major exposed sections, which refers to the torso and upper limbs, the sections with the greatest correlation with the overall thermal sensation in steady state were still the head, upper limbs, and lower limbs. This may be because when predicting thermal

sensation by skin temperature, not only the thermoreceptor density distribution but also the rate and amount of skin temperature changes with environmental parameters should be considered. Therefore, it is reasonable to establish the skin-related formula using the head, upper limbs, and lower limbs, which have high thermoreceptor densities and are sensitive to changes in environmental parameters as well as high thermal sensation weights. In summary, the head and torso, which account for approximately 70% of the weighting, are the sections with the most influence on the overall thermal sensation after using local cooling devices. When designing local cooling devices, the primary consideration could be cooling for these two sections (**Publication 4**).

## 4.2 Experimental uncertainty and limitation

In this study, a climate chamber was used to simulate warm conditions, focusing on the behavioral and psychological changes of the elderly by using three local cooling devices. However, considering the risk of disease and long-term medication, all the elderly recruited for this experiment were healthy; that is, their frailty was not considered. Moreover, the climate chamber's environment parameters were constant, whereas real environment parameters are always varying, and people may have more adaptative methods. Thus, the device-use models given in this study may not be accurate enough and need further field studies to validate. In addition, the weighting factors of local body parts were obtained in a steady state, thus, further validation needs to be done in transient conditions. Although the aim was to provide a reference for the indoor environment design of local residential and nursing homes for the elderly, as well as recommendations for the selection and control of local cooling devices for the elderly during the summer, the above contents could be considered limitations, and more research on the matter is needed in the future.

Local skin temperatures and thermal sensation were analyzed in detail in this study. However, because of the placement and directed flow pattern of the table fan and evaporative cooling device, the environmental parameters of the left and right sides of the human body were asymmetrical, which may have affected the results. The thermal manikin used in this experiment simulates an adult male with a height of 175cm, so the effective areas of the devices may differ for females. In addition, changes in skin temperature and thermal sensation over time were analyzed. However, the questionnaire was completed 15 min after the start of the local cooling phase, which is a slightly long interval for transient responses. Although it was challenging for the elderly participants to complete the questionnaire frequently, future research should attempt to shorten the time interval, particularly focusing the questionnaire fill-ins immediately following changes. It is important to note that in this study, convective local cooling used air at room temperature, and even for evaporative cooling, the temperature was slightly above the wet-bulb

temperature. Therefore, these results may not be suitable for cases involving stronger local cooling. In addition, this study recruited 26 participants, including 7 males and 19 females. Therefore, the results may be influenced by the imbalance in the sample. The impact of gender differences needs to be further considered in future research.

### **4.3 Recommendations for further research**

Healthy aging is a goal for future societies. Obviously, there is still a long way to go to achieve this objective. Regarding indoor thermal comfort of the elderly, future research directions can be considered from both theoretical and application aspects.

First, to improve the theoretical basis of indoor thermal comfort of elderly people, more climate chamber experiments are needed in the future. Through strict control of variables, the factors affecting the thermal comfort of the elderly can be objectively analyzed. To achieve this goal, more experimental conditions need to be set up, such as various temperatures from the cold side to the hot side, different humidity, different radiation temperature, etc. The experimental sample size needs to be increased, and the subjects might include different individual attributes as much as possible, such as different countries, different genders, different incomes, etc. The measurement of the subjects' physiological parameters also needs to be more detailed, such as measuring their health level, metabolic rate, body composition distribution, electroencephalography (EEG), etc. Health issues also require multidisciplinary research such as medicine science and engineering. At present, there is a gap in the research field of local thermal comfort of the elderly. It is necessary to conduct more experiments to explore how local thermal signals are integrated into overall thermal comfort. When this part of the gap is filled, it will promote the development of more PCS, and the existing PCS can also be optimized.

The conclusions derived from the climate chamber experiment are typically universal and can be broadly applied to the elderly population due to the strict control of the variables. However, in practical terms, there are significant differences in subjective feelings between individuals. When considering the practical application, longitudinal field studies on a small number of individuals may be more valuable. At present, micro-electro-mechanical systems have made significant progress, providing convenience for measuring environmental parameters and human physiological parameters. At the same time, the optimization and iteration of intelligent algorithms and the improvement of computer computing power complement each other and promote the development of artificial intelligence. The use of micro-sensors and artificial intelligence algorithms to monitor various physiological parameters of individuals in different

thermal environments and the use patterns of thermal-related equipment for a long time will be of great benefit to achieving individual thermal comfort in the future.

In addition to thermal comfort, the indoor environment needs to be comfortable in terms of acoustics and light, and air quality needs to be guaranteed. However, there are few related studies on the elderly, which deserves further exploration. Meanwhile, in addition to indoor thermal comfort, there is also outdoor thermal comfort matter. Outdoor exercise is also advocated by the policy of healthy aging. Therefore, it is necessary to ensure the health and well-being of the elderly outdoors.

## 5 Conclusions

In this thesis, the thermal response of the elderly in warm environments and the effect of different local cooling devices on maintaining their thermal comfort were studied through a series of climate chamber experiments with elderly people and a thermal manikin. Meanwhile, through the study of the internal relationship between physiology, psychology and behavior of the elderly, improvement suggestions for PCS and a reference for the control system of future smart homes are provided. The main goal of the thesis is to provide recommendations for maintaining indoor thermal comfort for older adults during heat waves or extreme heat events to reduce their heat-related morbidity and mortality.

### 5.1 Elderly people thermal response under different thermal conditions

The neutral temperature of the elderly from northern Europe was 26 °C, their preferred temperature was 26.5 °C, the upper limit of the acceptable temperature was 28 °C, and their thermal sensitivity was 0.324/°C. The lowest thermal acceptance rate was observed in environments with high temperature and relative humidity. The PMV model is more precise in predicting the thermal sensation of the elderly in a neutral thermal environment, while it will overestimate the thermal sensation of the elderly as the temperature rises. In addition, the elderly preferred an almost “no air movement” sensation in a neutral environment, and more air movement when the  $T_a$  increased.

The skin temperature of the upper back, forearm, palm, thigh, calf, and foot increased with  $T_a$  faster than that of other body parts, particularly the palm and foot, which had the highest coefficients, whereas the temperature of the pelvis and lower back seemed more stable. When the  $T_a$  rose, the skin temperature of the palm increased rapidly and reached the highest value ( $T_a = 32$  °C,  $T_{sk} = 36.1$  °C). This suggests that the limbs and extremities heat faster than other body parts and play a role in heat dissipation under warm conditions. Compared with young people, the skin temperature of the distal regions (head, hand, and foot) of elderly people was lower.

When  $T_a$  was higher than the preferred temperature and reached 27 °C, the device use rate was approximately 50%, and the lower mode was mainly used. When

$T_a$  was close to the upper limit at 28 °C, the lower mode use rate was highest at approximately 60%. As  $T_a$  increased to 30.5 °C, the higher mode use rate eventually surpassed lower mode.

The significant differences between females and males in terms of torso skin temperature, lower limb skin temperature, and tympanic temperature were observed. However, there were no significant differences in the physiological parameters between the normal weight groups. Due to large individual differences, no significant differences in thermal preference and average device power usage between the gender and BMI groups were detected.

## 5.2 The effectiveness of three local cooling devices

The table fan provided the narrowest range of  $T_{eq}$  (28.1–28.3 °C at 29 °C and 31.7–31.9 °C at 32 °C), followed by the air-cooled jacket (27.4–28.4 °C at 29 °C and 31.3–31.6 °C at 32 °C). The evaporative cooling device offered the widest  $T_{eq}$  range (27.2–28.8 °C at 29 °C and 30.5–31.4 °C at 32 °C). When wearing the air-cooled jacket without using it,  $T_{eq}$  reached 29.8 °C in the 29 °C condition and 32.4 °C in the 32 °C condition, reflecting the jacket's inherent clothing insulation (around 0.19 clo).

Elderly people, after using local cooling devices in different thermal environments, exhibited stable physiological parameters within 10 minutes. The mean skin temperature decreased by no more than 0.5 °C, with a local skin temperature reduction ranging from 0.5 °C to 1.1 °C. Skin temperature significantly dropped in exposed body parts, while the unexposed parts remained nearly unchanged.

After using the three devices, the skin temperature of the exposed body parts decreased significantly, bringing them closer to their neutral zones, whereas the skin temperature of the unexposed parts remained nearly constant, deviating more from their neutral values than the exposed parts. This indicates that the local cooling devices used in this study can only adjust the skin temperature of the exposed parts. The unexposed parts, including the lower back for the table fan and evaporative cooling device and the palm for the air-cooled jacket, had the highest skin temperature.

Thermal and air movement sensation varied markedly within the first 15 min and subsequently stabilized. Local thermal sensations in both exposed and unexposed body parts of the elderly significantly decreased. However, this may be attributed to the longer questionnaire interval, causing the overall thermal sensation to influence local thermal sensation.

At 28 °C (60%) and 29 °C (40%), the use of a table fan, evaporative cooling device, or air-cooled jacket could reduce the elderly's thermal sensation to neutral and make more than 80% of people accept the thermal condition. At 33 °C (40%) and 32 °C (50%), the use of an evaporative cooling device or air-cooled jacket

reduced thermal sensation significantly, but not to a neutral state. Although thermal acceptance rates increased after using all devices, they were less than 80%, except at 33 °C (40%), when evaporative cooling was used. Furthermore, all three devices performed better under conditions with lower relative humidity.

After using all experimental local cooling devices, the acceptance rate of air movement declined. When the air movement was higher, it disturbed the elderly and caused physical discomfort. In addition, there were more individual differences in air movement preference than in thermal preference.

### **5.3 The relationship between skin temperature, thermal sensation, and device usage behaviour**

Under steady state, in a uniform environment, skin temperatures of all parts except the pelvis and lower back showed strong correlation with their corresponding local thermal sensation. In a non-uniform environment (using a table fan, evaporative cooler, or air-cooled jacket), only skin temperatures of the limbs and extremities showed stronger correlation with their corresponding local thermal sensation.

After using local cooling devices, skin temperatures of the head, limbs, and extremities exhibited stronger correlation with overall thermal sensation, indicating the importance of considering sensitive extremities when predicting thermal sensation in non-uniform environments. Changes in skin temperature in exposed areas show a strong correlation with changes in overall thermal sensation.

Older adults' thermal sensations were generally consistent with their device usage as the larger the TSV was, the greater the device usage power also was. This trend was most evident when the TSV of older adults was at a high level, and it gradually weakened with an increase in the time spent using the cooling device.

Skin temperature and device usage had a complex causal relationship, and the cross-lagged effect between the two was the most significant at 5-minute intervals. When using the LSTM model to predict the speed of local cooling devices, it had an accuracy of approximately 70% when the input variable was the head and wrist skin temperature. When the input variable was device usage, the accuracy was 85%. When the input variable included the head and wrist skin temperature and device usage, the accuracy was 90%.

### **5.4 The effectiveness of the novel PCS**

Results from factor analysis of local thermal sensations reveal that the human body can be divided into four sections after using three different devices: head (forehead), torso (chest, pelvis, upper back, lower back), upper limbs (forearm, palm), and lower limbs (thigh, calf, and foot). The thermal sensation weights of the head and torso sections have the greatest impact on overall thermal sensation, constituting

approximately 70%. When designing local cooling devices, priority should be given to cooling these areas.

Using the ventilated jacket with the chair PCS resulted in substantial reductions in both skin temperature and elderly thermal sensation, surpassing the performance of the individual chair PCS systems, especially under hot room conditions (33 °C). In a warm room with a temperature of 29 °C, the integrated mode of the system shifted elderly thermal sensation from slightly warm to between neutral and slightly cool. In a hot room with a temperature of 33 °C, the integrated mode of the system resulted in notably improved elderly thermal sensation, shifting from warm and hot to neutral and slightly warm.

Operating the chair PCS at 21 l/s and the ventilated jacket at 11 l/s achieved similar thermal sensation to the case when the chair alone is used at 34 l/s supply. Thus, employing the jacket has led to a notable 19% reduction in electric energy consumption while maintaining similar elderly thermal sensation.

## References

- Aryal, A., & Becerik-Gerber, B. (2019). A comparative study of predicting individual thermal sensation and satisfaction using wrist-worn temperature sensor, thermal camera and ambient temperature sensor. *Building and Environment*, 160.
- ASHRAE. (2021). ANSI/ASHRAE Addendum d to ANSI/ASHRAE Standard 55-2020 Thermal Environmental Conditions for Human Occupancy.
- Atmaca, I., & Yigit, A. (2006). Predicting the effect of relative humidity on skin temperature and skin wettedness. *Journal of Thermal Biology*, 31, 442–452.
- Bekryaev, R. V., Polyakov, I. V., & Alexeev, V. A. (2010). Role of polar amplification in long-term surface air temperature variations and modern arctic warming. *Journal of Climate*, 23, 3888–3906.
- Berglund, L. G., & Gonzalez, R. R. (1977). Evaporation of sweat from sedentary man in humid environments. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology*, 42, 767–772.
- Boerstra, A. C., Kulve, M. te, Toftum, J., Loomans, M. G. L. C., Olesen, B. W., & Hensen, J. L. M. (2015). Comfort and performance impact of personal control over thermal environment in summer: Results from a laboratory study. *Building and Environment*, 87, 315–326.
- Brinell, H., & Cabanac, M. (1989). Tympanic temperature is a core temperature in humans. *Journal of Thermal Biology*, 14, 47–53.
- Browne, M. W., & Cudeck, R. (1992). Alternative Ways of Assessing Model Fit. *Sociological Methods & Research*, 21, 230–258.
- Ciuha, U., & Mekjavic, I. B. (2016). Regional thermal comfort zone in males and females. *Physiology and Behavior*, 161, 123–129.
- Demeritt, D. (2001). The construction of global warming and the politics of science. *Annals of the Association of American Geographers*, 91, 307–337.
- Du, H., Zhao, Z., Lyu, J., Li, J., liu, Z., Li, X., Yang, Y., Lan, L., & Lian, Z. (2023). Gender differences in thermal comfort under coupled environmental factors. *Energy and Buildings*, 295.
- Ebi, K. L., Capon, A., Berry, P., Broderick, C., de Dear, R., Havenith, G., Honda, Y., Kovats, R. S., Ma, W., Malik, A., Morris, N. B., Nybo, L., Seneviratne, S. I., Vanos, J., & Jay, O. (2021). Hot weather and heat extremes: health risks. In *The Lancet* (Vol. 398, Issue 10301, pp. 698–708).
- El-Fil, B., Ghaddar, N., & Ghali, K. (2016). Optimizing performance of ceiling-mounted personalized ventilation system assisted by chair fans: Assessment of thermal comfort and indoor air quality. *Science and Technology for the Built Environment*, 22, 412–430.

- Farahani, A. V., Jokisalo, J., Korhonen, N., Jylhä, K., Ruosteenoja, K., & Kosonen, R. (2021). Overheating risk and energy demand of nordic old and new apartment buildings during average and extreme weather conditions under a changing climate. *Applied Sciences (Switzerland)*, 11.
- Feng, Y., Liu, S., Wang, J., Yang, J., Jao, Y. L., & Wang, N. (2022). Data-driven personal thermal comfort prediction: A literature review. In *Renewable and Sustainable Energy Reviews (Vol. 161)*.
- Fiala, D. (1998). *Dynamic Simulation of Human Heat Transfer and Thermal Comfort*.
- Foda, E., & Sirén, K. (2011). A new approach using the Pierce two-node model for different body parts. *International Journal of Biometeorology*, 55, 519–532.
- Garcia-Souto, M. D. P., & Dabnichki, P. (2013). Skin temperature distribution and thermoregulatory response during prolonged seating. *Building and Environment*, 69, 14–21.
- Griefahn, B., & Künemund, C. (2001). The effects of gender, age, and fatigue on susceptibility to draft discomfort. *Journal of Thermal Biology*, 26, 395–400.
- Guergova, S., & Dufour, A. (2011). Thermal sensitivity in the elderly: A review. In *Ageing Research Reviews (Vol. 10, pp. 80–92)*.
- Hardy, J. D., Du Bois, E. F., & Soderstrom, G. F. (1938). The Technic of Measuring Radiation and Convection. *The Journal of Nutrition*, 15, 461–475.
- He, Y., Chen, W., Wang, Z., & Zhang, H. (2019). Review of fan-use rates in field studies and their effects on thermal comfort, energy conservation, and human productivity. In *Energy and Buildings (Vol. 194, pp. 140–162)*. Elsevier Ltd.
- He, Y., Li, N., Wang, X., He, M., & He, D. (2017). Comfort, energy efficiency and adoption of personal cooling systems in warm environments: A field experimental study. *International Journal of Environmental Research and Public Health*, 14.
- He, Y., Parkinson, T., Arens, E., Zhang, H., Li, N., Peng, J., Elson, J., & Maranville, C. (2022). Creating alliesthesia in cool environments using personal comfort systems. *Building and Environment*, 209.
- Healy, J. D., & Peter Clinch, J. (2002). Fuel poverty, thermal comfort and occupancy: Results of a national household - survey in Ireland. *Applied Energy*, 73, 329–343.
- Hirata, A., Nomura, T., & Laakso, I. (2015). Computational estimation of body temperature and sweating in the aged during passive heat exposure. *International Journal of Thermal Sciences*, 89, 154–163.
- Hu, L. T., & Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling*, 6, 1–55.
- Huang, L., Ouyang, Q., Zhu, Y., & Jiang, L. (2013). A study about the demand for air movement in warm environment. *Building and Environment*, 61, 27–33.
- Huizenga, C., Zhang, H., Arens, E., & Wang, D. (2004). Skin and core temperature response to partial- and whole-body heating and cooling. *Journal of Thermal Biology*, 29, 549–558.

- Hwang, R. L., & Chen, C. P. (2010). Field study on behaviors and adaptation of elderly people and their thermal comfort requirements in residential environments. *Indoor Air*, 20, 235–245.
- Indraganti, M., Ooka, R., & Rijal, H. B. (2015). Thermal comfort in offices in India: Behavioral adaptation and the effect of age and gender. *Energy and Buildings*, 103, 284–295.
- Inoue, Y., Nakao, M., Araki, T., & Murakami, H. (1991). Regional differences in the sweating responses of older and younger men. *Journal of Applied Physiology*, 71, 2453–2459.
- Itani, M., Ghaddar, N., Ghali, K., & Laouadi, A. (2020). Bioheat modeling of elderly and young for prediction of physiological and thermal responses in heat-stressful conditions. *Journal of Thermal Biology*, 88.
- Jian, Y., Liu, J., Pei, Z., & Chen, J. (2022). Occupants' tolerance of thermal discomfort before turning on air conditioning in summer and the effects of age and gender. *Journal of Building Engineering*, 50.
- Jiao, Y., Yu, H., Yu, Y., Wang, Z., & Wei, Q. (2020). Adaptive thermal comfort models for homes for older people in Shanghai, China. *Energy and Buildings*, 215.
- Jin, Q., Li, X., Duanmu, L., Shu, H., Sun, Y., & Ding, Q. (2012). Predictive model of local and overall thermal sensations for non-uniform environments. *Building and Environment*, 51, 330–344.
- Jokisalo, J., Pajunen, S., Kravchenko, I., Kilpeläinen, S., Kosonen, R., Farahani, A. V., & Korhonen, N. (2021). Toteutuneet kesäaikaiset huonelämpötilat helsinkiläisissä kerrostaloissa.
- Kainaga, T., Sagisaka, K., Yamada, R., & Nakaya, T. (2022). 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.
- Karaki, W., Ghaddar, N., Ghali, K., Kuklane, K., Holmér, I., & Vanggaard, L. (2013). Human thermal response with improved AVA modeling of the digits. *International Journal of Thermal Sciences*, 67, 41–52.
- Karjalainen, S. (2007). Gender differences in thermal comfort and use of thermostats in everyday thermal environments. *Building and Environment*, 42, 1594–1603.
- Kenney, W. L., & Munce, T. A. (2003). Aging and human temperature regulation. In *Journal of Applied Physiology* (Vol. 95, pp. 2598–2603). American Physiological Society.
- Kim, J., Zhou, Y., Schiavon, S., Raftery, P., & Brager, G. (2018). Personal comfort models: Predicting individuals' thermal preference using occupant heating and cooling behavior and machine learning. *Building and Environment*, 129, 96–106.
- Laouadi, A. (2022). A New General Formulation for the PMV Thermal Comfort Index. *Buildings*, 12.
- Liu, W., Lian, Z., Deng, Q., & Liu, Y. (2011). Evaluation of calculation methods of mean skin temperature for use in thermal comfort study. *Building and Environment*, 46, 478–488.
- Luo, M., Cao, B., Ji, W., Ouyang, Q., Lin, B., & Zhu, Y. (2016). The underlying linkage between personal control and thermal comfort: Psychological or physical effects? *Energy and Buildings*, 111, 56–63.

- Maivel, M., Kurnitski, J., & Kalamees, T. (2015). Field survey of overheating problems in Estonian apartment buildings. *Architectural Science Review*, 58, 1–10.
- Meade, R. D., Notley, S. R., Kirby, N. V., & Kenny, G. P. (2024). A critical review of the effectiveness of electric fans as a personal cooling intervention in hot weather and heatwaves. In *The Lancet Planetary Health* (Vol. 8, pp. e256–e269). Elsevier B.V.
- Nadel, E. R., Mitchell, J. W., & Stolwijk, J. A. J. (1973). Differential thermal sensitivity in the human skin. *Pflügers Archiv: European Journal of Physiology*, 340, 71–76.
- Navarrete-Villanueva, D., Gómez-Cabello, A., Marín-Puyalto, J., Moreno, L. A., Vicente-Rodríguez, G., & Casajús, J. A. (2021). Frailty and Physical Fitness in Elderly People: A Systematic Review and Meta-analysis. In *Sports Medicine* (Vol. 51, pp. 143–160). Springer Science and Business Media Deutschland GmbH.
- Neziri, A. Y., Curatolo, M., Nüesch, E., Scaramozzino, P., Andersen, O. K., Arendt-Nielsen, L., & Jüni, P. (2011). Factor analysis of responses to thermal, electrical, and mechanical painful stimuli supports the importance of multi-modal pain assessment. *Pain*, 152, 1146–1155.
- Ole Fanger, P., & Toftum, J. (2002). Extension of the PMV model to non-air-conditioned buildings in warm climates. *Energy and Buildings*, 34, 533–536.
- Park, S., Hellwig, R. T., Grün, G., & Holm, A. (2011). Local and overall thermal comfort in an aircraft cabin and their interrelations. *Building and Environment*, 46, 1056–1064.
- Peng, C. (2010). Survey of thermal comfort in residential buildings under natural conditions in hot humid and cold wet seasons in Nanjing. *Frontiers of Architecture and Civil Engineering in China*, 4, 503–511.
- Peng, Y., Feng, T., & Timmermans, H. J. P. (2021). Heterogeneity in outdoor comfort assessment in urban public spaces. *Science of the Total Environment*, 790.
- Rana, R., Kusy, B., Jurdak, R., Wall, J., & Hu, W. (2013). Feasibility analysis of using humidex as an indoor thermal comfort predictor. *Energy and Buildings*, 64, 17–25.
- Rida, M., Ghaddar, N., Ghali, K., & Hoballah, J. (2014). Elderly bioheat modeling: changes in physiology, thermoregulation, and blood flow circulation. *International Journal of Biometeorology*, 58, 1825–1843.
- Rissetto, R., Schweiker, M., & Wagner, A. (2021). Personalized ceiling fans: Effects of air motion, air direction and personal control on thermal comfort. *Energy and Buildings*, 235.
- Romanovsky, A. A. (2014). Skin temperature: Its role in thermoregulation. In *Acta Physiologica* (Vol. 210, pp. 498–507).
- Salehi, B., Ghanbaran, A. H., & Maerefat, M. (2020). Intelligent models to predict the indoor thermal sensation and thermal demand in steady state based on occupants' skin temperature. *Building and Environment*, 169.
- Schellen, L., van Marken Lichtenbelt, W. D., Loomans, M. G. L. C., Toftum, J., & de Wit, M. H. (2010). Differences between young adults and elderly in thermal comfort, productivity, and thermal physiology in response to a

- moderate temperature drift and a steady-state condition. *Indoor Air*, 20, 273–283.
- Soebarto, V., Zhang, H., & Schiavon, S. (2019). A thermal comfort environmental chamber study of older and younger people. *Building and Environment*, 155, 1–14.
- Song, W., Zhong, F., Calautit, J. K., & Li, J. (2024). Exploring the role of skin temperature in thermal sensation and thermal comfort: A comprehensive review. In *Energy and Built Environment*. KeAi Communications Co.
- Stevens, J. C., & Choo, K. K. (1998). Temperature sensitivity of the body surface over the life span. *Somatosensory and Motor Research*, 15, 13–28.
- Streiner, D. L. (2005). Finding our way: An introduction to path analysis. In *Canadian Journal of Psychiatry* (Vol. 50, pp. 115–122). Canadian Psychiatric Association.
- Takahashi, Y., Nomoto, A., Yoda, S., Hisayama, R., Ogata, M., Ozeki, Y., & Tanabe, S. ichi. (2021). Thermoregulation model JOS-3 with new open source code. *Energy and Buildings*, 231.
- Tanabe, S., Arens, E. A., Bauman, F., Zhang, H., & Madsen, T. (1994). Evaluating thermal environments by using a thermal manikin with controlled skin surface temperature.
- Tejero-González, A., & Esquivias, P. M. (2019). Personalized evaporative cooler to reduce energy consumption and improve thermal comfort in free-running spaces. *Sustainability (Switzerland)*, 11.
- Tikuisis, P., Meunier, P., & Jubenville, C. E. (2001). Human body surface area: Measurement and prediction using three dimensional body scans. *European Journal of Applied Physiology*, 85, 264–271.
- Tipaldo, J. F., Balk, D., & Hunter, L. M. (2024). A framework for ageing and health vulnerabilities in a changing climate. In *Nature Climate Change*. Nature Research.
- Toftum, J., Melikov, A., Tynel, A., Bruzda, M., & Fanger, P. O. (2003). Human response to air movement—evaluation of ashrae’s draft criteria (rp-843). *HVAC and R Research*, 9, 187–202.
- Van Hoof, J., Kort, H. S. M., Hensen, J. L. M., Duijnste, M. S. H., & Rutten, P. G. S. (2010). Thermal comfort and the integrated design of homes for older people with dementia. *Building and Environment*, 45, 358–370.
- Van Hoof, J., Kort, H. S. M., & van Waarde, H. (2009). Housing and care for older adults with dementia: A European perspective. *Journal of Housing and the Built Environment*, 24, 369–390.
- Van Someren, E. J. W. (2007). Thermoregulation and aging. In *American Journal of Physiology - Regulatory Integrative and Comparative Physiology* (Vol. 292).
- Wang, L., Chen, M., & Chen, Z. (2019). Local thermal discomfort in low temperature environments. *Thermal Science*, 23, 2211–2218.
- Wang, L., Ren, X., Zhu, X., Li, W., Yang, J., Zhang, H., Yang, J., & Yin, H. (2023). Effects of body muscle and fat on differences in thermal preference. *Building and Environment*, 243.
- Wang, Y., Zhou, J., Chen, K., Wang, Y., & Liu, L. (2017). Water quality prediction method based on LSTM neural network. *Proceedings of the 2017 12th*

International Conference on Intelligent Systems and Knowledge Engineering, ISKE 2017, 2018-January, 1–5.

- Wang, Z., de Dear, R., Luo, M., Lin, B., He, Y., Ghahramani, A., & Zhu, Y. (2018). Individual difference in thermal comfort: A literature review. In *Building and Environment* (Vol. 138, pp. 181–193). Elsevier Ltd.
- Wang, Z., Zhang, H., He, Y., Luo, M., Li, Z., Hong, T., & Lin, B. (2020). Revisiting individual and group differences in thermal comfort based on ASHRAE database. *Energy and Buildings*, 219.
- Wu, Q., Liu, J., Zhang, L., Zhang, J., & Jiang, L. (2020). Study on thermal sensation and thermal comfort in environment with moderate temperature ramps. *Building and Environment*, 171.
- Wu, Y., Liu, H., Li, B., Kosonen, R., Kong, D., Zhou, S., & Yao, R. (2019). Thermal adaptation of the elderly during summer in a hot humid area: Psychological, behavioral, and physiological responses. *Energy and Buildings*, 203.
- Xie, J., Li, H., Li, C., Zhang, J., & Luo, M. (2020). Review on occupant-centric thermal comfort sensing, predicting, and controlling. In *Energy and Buildings* (Vol. 226). Elsevier Ltd.
- Xiong, J., Ma, T., Lian, Z., & de Dear, R. (2019). Perceptual and physiological responses of elderly subjects to moderate temperatures. *Building and Environment*, 156, 117–122.
- Xiong, J., Zhou, X., Lian, Z., You, J., & Lin, Y. (2016). Thermal perception and skin temperature in different transient thermal environments in summer. *Energy and Buildings*, 128, 155–163.
- Yang, H., Deng, Y., Cao, B., & Zhu, Y. (2020). Study on the local and overall thermal perceptions under nonuniform thermal exposure using a cooling chair. *Building and Environment*, 176.
- Yao, Y., Lian, Z., Liu, W., & Shen, Q. (2007). Experimental study on skin temperature and thermal comfort of the human body in a recumbent posture under uniform thermal environments. *Indoor and Built Environment*, 16, 505–518.
- Yoshida, A., Hisabayashi, T., Kashihara, K., Kinoshita, S., & Hashida, S. (2015). Evaluation of effect of tree canopy on thermal environment, thermal sensation, and mental state. *Urban Climate*, 14, 240–250.
- Younes, J., Chen, M., Ghali, K., Kosonen, R., Melikov, A. K., & Ghaddar, N. (2023). A thermal sensation model for elderly under steady and transient uniform conditions. *Building and Environment*, 227.
- Younes, J., Chen, M., Ghali, K., Kosonen, R., Melikov, A. K., Kilpeläinen, S., & Ghaddar, N. (2024). Enhancing thermal comfort of older adults during extreme weather: Combined personal comfort system and ventilated vest. *Energy and Buildings*, 318.
- Yun, G. Y. (2018). Influences of perceived control on thermal comfort and energy use in buildings. *Energy and Buildings*, 158, 822–830.
- Zhai, Y., Zhang, H., Zhang, Y., Pasut, W., Arens, E., & Meng, Q. (2013). Comfort under personally controlled air movement in warm and humid environments. *Building and Environment*, 65, 109–117.
- Zhang, H., Arens, E., Huizenga, C., & Han, T. (2010). Thermal sensation and comfort models for non-uniform and transient environments, part III:

- Whole-body sensation and comfort. *Building and Environment*, 45(2), 399–410.
- Zhang, H., Arens, E., & Zhai, Y. (2015). A review of the corrective power of personal comfort systems in non-neutral ambient environments. *Building and Environment*, 91, 15–41.
- Zhang, S., & Zhu, N. (2022). Gender differences in thermal responses to temperature ramps in moderate environments. *Journal of Thermal Biology*, 103.
- Zhang, Y., & Zhao, R. (2007). Effect of local exposure on human responses. *Building and Environment*, 42, 2737–2745.
- Zhao, Q., Lyu, J., Du, H., Lian, Z., & Zhao, Z. (2023). Gender differences in thermal sensation and skin temperature sensitivity under local cooling. *Journal of Thermal Biology*, 111.
- Zhou, S., Li, B., Du, C., Liu, H., Wu, Y., Hodder, S., Chen, M., Kosonen, R., Ming, R., Ouyang, L., & Yao, R. (2023). Opportunities and challenges of using thermal comfort models for building design and operation for the elderly: A literature review. In *Renewable and Sustainable Energy Reviews* (Vol. 183). Elsevier Ltd.

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