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**DESIGN AND EVALUATION OF  
PERSONAL COOLING GARMENTS**

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**PhD**

**The Hong Kong Polytechnic University**

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**The Hong Kong Polytechnic University**  
**School of Fashion and Textiles**

**Design and Evaluation of Personal Cooling Garments**

**ZHOU Yiying**

**A thesis submitted in partial fulfilment of the requirements  
for the degree of Doctor of Philosophy**

**June 2025**

# **CERTIFICATE OF ORIGINALITY**

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## **Abstract**

Personal cooling garments have gained significant attention due to the need for alleviating heat stress and improving thermal comfort in various occupational and personal settings. This thesis presents a comprehensive investigation of personal cooling garments (PCGs), focusing on the design, development, and evaluation of novel cooling solutions. Two PCGs are developed and evaluated: The Wearable Cooling and Dehumidifying System (WCDS) for healthcare workers wearing personal protective equipment (PPE) and Ventilation Cooling Garment (VCG) for individuals working in hot environments.

The literature review categorizes personal cooling technologies according to their fundamental mechanisms: air cooling, evaporative cooling, phase-change cooling, liquid cooling, thermoelectric cooling, and radiative cooling. For each category, the review analyzes critical design parameters and applications while systematically identifying their advantages and limitations. Quantitative performance parameters enable objective comparisons across different cooling technologies. The review further included standardized evaluation methodologies, establishing a foundation for future PCG development.

For the Wearable Cooling and Dehumidifying System (WCDS), development began with identifying critical requirements for healthcare workers: effective cooling capacity,

humidity control, infection prevention, and PPE compatibility. A fundamental innovation was addressing both temperature and humidity regulation simultaneously within the enclosed PPE microenvironment—a crucial need not adequately addressed by existing commercial solutions.

Thermal manikin testing demonstrated the WCDS's cooling efficiency, delivering consistent cooling power of approximately 60 Watts over 4 hours—2.9 to 3.9 times higher per unit weight than commercial alternatives. While liquid cooling garments (LCG) and phase-change cooling garments (PCCG) exhibited declining performance, the WCDS maintained steady cooling while effectively reducing both temperature and humidity within PPE. Human subject testing revealed significant physiological benefits, with the WCDS maintaining lower core temperatures during exercise without increased cardiovascular strain, while substantially improving thermal comfort and reducing wetness sensation.

The Ventilation Cooling Garment (VCG) design process involved comprehensive requirements analysis for hot environment applications, prioritizing optimized airflow distribution to physiologically critical regions, particularly the scapular area, while maintaining energy efficiency and minimizing noise. The design strategically balanced cooling effectiveness with practical limitations of power consumption, user comfort and practical wearability. Comparative analysis showed the VCG delivered approximately 85% higher cooling power at low airflow rates compared to commercial air cooling

garments (ACG), with optimal efficiency at lower fan speeds—indicating potential for reduced energy consumption without compromising effectiveness.

In human trials, the VCG maintained core temperature differences of approximately 0.2°C and reduced heart rates by approximately 8 bpm during exercise compared to non-cooling conditions. Microclimate temperatures were consistently 3°C lower, with maximum cooling effect in the scapular region. Perceived exertion decreased by 40-50% with the cooling garment.

The research establishes a methodological framework combining systematic design processes, material selection, prototype development, and comprehensive performance evaluation for developing personal cooling technologies tailored to specific occupational requirements. Future research directions include further design optimization, material innovations, extended field testing, standardization of evaluation methodologies, and expansion to other applications. These findings have significant implications for occupational health and safety, worker productivity, and comfort in thermally challenging workplaces.

## Publications

1. **Zhou Y**, Lou L, Fan J. Assessment of Wearable Cooling and Dehumidifying System Used under Personal Protective Clothing through Human Subject Testing[J]. *Processes*, 2024, 12(6): 1126.
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4. Lou, L., **Zhou, Y.**, Yan, Y., Hong, Y., & Fan, J. (2022). Wearable cooling and dehumidifying system for personal protective equipment (PPE). *Energy and Buildings*, 276, 112510.
5. Lou, L., Wu, Y. S., **Zhou, Y.**, & Fan, J. (2022). Effects of body positions and garment design on the performance of a personal air cooling/heating system. *Indoor air*, 32(1), e12921.
6. Chai, J., Kang, Z., Yan, Y., Lou, L., **Zhou, Y.**, & Fan, J. (2022). Thermoregulatory clothing with temperature-adaptive multimodal body heat regulation. *Cell Reports Physical Science*, 3(7), 100958.

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Through my doctoral journey, I have discovered that life is complex and beautiful, filled with moments of joy and sorrow. Before this amazing experience, I was often trapped in negative emotions, clouding my perception of the world. However, as I involved myself in my studies, I began to grow with self-acceptance, embracing my strengths and weaknesses. This personal growth has allowed me to extend understanding to myself and those around me. As a result, my life now filled with the rich colors of joy and love.

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## List of Abbreviations

PCGs	Personal cooling garments
WCDS	Wearable cooling and dehumidifying system
ACGs	Air cooling garments
ECGs	Evaporative cooling garments
PCCGs	Phase-change cooling garments
PCMs	Phase-change materials
LCGs	Liquid cooling garments
TCGs	Thermoelectric cooling garments
RCGs	Radiative cooling garments
MS	Multiple sclerosis
RH	Relative humidity
TE	Thermoelectric
R <sub>ct</sub>	Thermal insulation
R <sub>et</sub>	Evaporative resistance
EVA	Extravehicular activity
PeSI	Perceptual strain index
PhSI	Physiological strain index
RPE	Rating of perceived exertion
PPE	Personal protective equipment
PPC	Personal protective clothing
PCSs	Personal Cooling Systems
ACMR	Air cooling & moisture-removal
VCG	Ventilation cooling garment

# Chapter 1 Introduction

## 1.1 Research background

Heat stress has become a serious problem in numerous occupational settings, both outdoors and indoors [1, 2]. When heat exposure exceeds an individual's thermoregulatory capacity, heat accumulates in the human body. Occupational workers are particularly vulnerable when performing highly physical activities, working under hot-humid environmental conditions, or wearing impermeable protective clothing that increases heat strain. The resulting heat accumulation may lead to a higher risk of heat-related illnesses and diseases, including dehydration, heat stroke, chronic kidney injuries, or even death [3-9]. To mitigate the impacts of occupational heat strain, researchers have investigated various heat mitigation strategies to ensure the safety and health of workers, including adjusting activity levels, planning breaks, modifying work environments, optimizing clothing, and using personal cooling garments (PCGs) [10-13]. Among these solutions, PCGs have proven to be an effective cooling measure for occupational workers to manage their thermal state, satisfy individual thermal comfort needs, and improve working performance [14, 15].

Researchers are constantly designing, testing, and optimizing PCGs to minimize occupational heat stress. PCGs can be classified based on the cooling techniques employed, with air cooling garments, phase change cooling garments, and liquid cooling garments being the three most common types [16, 17]. Other types of PCGs,

such as radiative cooling garments, thermoelectric cooling garments, and evaporative cooling garments, have also been proposed [18-21]. However, most of the designed cooling garments remain in the research phase and face significant commercialization challenges due to limitations such as excessive weight, comfort issues, inadequate cooling duration, and integration difficulties with required work attire. These limitations underscore the need for continued research and development of more practical PCG solutions tailored to specific occupational scenarios.

Various methods have been employed to evaluate PCGs, including thermal manikin tests, human trials, and model simulations [22]. Thermal manikins serve as reliable and accurate instruments to evaluate overall clothing systems by assessing the thermal and evaporative factors between the ambient environment and the human body [23]. Human subject tests can be conducted independently or combined with thermal manikins to provide complementary data on physiological responses and subjective comfort. Additionally, human thermoregulatory models have been developed to simulate human thermophysiological responses in different environmental settings, offering a theoretical framework for PCG design optimization [24-27].

This research aims to address the limitations of existing PCGs by developing an innovative cooling technique with optimized garment design that balances cooling effectiveness, wearability, and practical implementation. Specifically, the study seeks to create a more effective, comfortable, and practical PCG suitable for a wide range of

occupational settings. The designed PCG will be systematically evaluated using both thermal manikin tests and human trials to comprehensively assess its cooling performance, wearability, and user experience under conditions that simulate real occupational challenges. The findings of this research will contribute to the advancement of PCG technology and provide valuable insights for future research and development in the field of personal thermal management for occupational workers, ultimately enhancing the safety, comfort, and productivity of workers in thermally challenging environments.

## **1.2 Research objectives**

As thermoregulation is essential for personal comfort and safety, and thermal sensitivity varies significantly between individuals, this research aims to design, develop, and validate innovative personal cooling systems for specific occupational scenarios. The objectives of this study are:

1. To design and develop an innovative personal cooling system specifically tailored for healthcare workers wearing protective clothing in indoor hospital environments, incorporating novel cooling technologies that address the unique medical settings including infection control requirements, mobility needs, and shift duration.
2. To evaluate the thermal and evaporative properties of the newly designed healthcare

cooling system in comparison with commercially available cooling garments through thermal manikin testing, quantifying cooling capacity, duration and efficiency under simulated hospital environmental conditions.

3. To assess the effectiveness of the healthcare cooling system through human subject trials measuring both physiological parameters (skin temperature, core temperature and heart rate) and subjective responses (thermal comfort, movement restriction and usability) during simulated healthcare tasks intensity.

4. To translate knowledge gained from the healthcare cooling system development to design a second-generation personal cooling garment optimized for outdoor workers exposed to higher environmental temperature and higher metabolic workloads.

5. To characterize the thermal performance of the outdoor worker cooling garment compared with commercial air cooling garment under different settings through thermal manikin testing.

6. To validate the outdoor cooling garment's effectiveness through human subject trials in controlled hot environments, measuring physiological responses (skin and core temperatures, heart rate) and psychological parameters (thermal comfort, perceived exertion, wearing comfort and thermal preference) during standardized treadmill protocols.

7. To provide evidence-based recommendations for the implementation of the developed personal cooling systems in healthcare and outdoor work settings, considering factors such as work intensity, environmental conditions, and individual characteristics, to optimize the safety and well-being of workers exposed to heat stress.

### **1.3 Research significance**

The research significance of this study lies in its potential to address the issue of occupational heat stress and its impact on the health, safety, and productivity of workers in various industries. By focusing on the development and evaluation of innovative personal cooling systems for healthcare workers in indoor conditions and outdoor workers in hot environments, this work aims to provide practical solutions to mitigate the risks associated with heat strain in these challenging work environments. The significance can be highlighted in several key aspects:

1. Enhancing worker safety and well-being: The development of effective and user-friendly personal cooling systems contributes directly to preventing heat-related illnesses and injuries among occupational workers, who frequently experience high levels of heat stress due to hot environments, protective clothing requirements and physically demanding tasks.

2. Improving work performance and productivity: Effective personal cooling systems

help maintain optimal thermal comfort, reducing heat stress impacts on physical performance. Beyond the individual productivity, this can also decrease medical costs and fewer workplace accidents in thermally challenging environments.

3. Advancing personal thermal management technology: This research aims to push the boundaries of current PCG technology by exploring innovative cooling techniques, materials, and designs. The findings will contribute to the development of more efficient, comfortable, and practical PCGs with applications extending beyond the studied occupations to other heat-stressed populations.

4. Informing occupational health and safety guidelines: The quantitative and qualitative data generated from this research can directly inform and update occupational health and safety guidelines related to heat stress management.

5. Establishing foundations for future research: The methodologies and findings developed provide a foundation for future personal thermal management research. The insights gained can be applied to other occupational settings and adapted for vulnerable populations such as the elderly and individuals with chronic health conditions.

## **1.4 Thesis outline**

Chapter 1 provides an overview of the research background, highlighting the

importance of personal cooling garments in mitigating heat stress and improving thermal comfort. The research objectives are clearly stated, focusing on the development and assessment of novel cooling garments for healthcare workers in indoor conditions and outdoor workers in hot environments. The significance of the research is discussed, emphasizing the potential impact on occupational health and safety, working performance and technical improvement in personal thermal management. Finally, the thesis outline is presented, providing an overview for the thesis.

Chapter 2 presents a comprehensive literature review beginning with an introduction to the current state of personal cooling garments. It systematically classifies and analyzes design parameters of different cooling technologies, including air cooling, evaporative cooling, phase-change cooling, liquid cooling, thermoelectric cooling, and radiative cooling. A quantitative comparison of cooling performance across different PCG types establishes baseline for evaluation. The chapter explores applications and specialized designs for nine distinct occupational working scenarios, highlighting the unique thermal challenges and requirements of each. Evaluation methodologies for cooling garments are critically assessed, including thermal manikin testing protocols, human trial approaches, and thermoregulatory modeling techniques. The chapter concludes by identifying specific knowledge gaps that this research addresses.

Chapter 3 focuses on the design and development of a wearable cooling and

dehumidifying system (WCDS) for healthcare workers. The chapter establishes comprehensive design requirements categorized into functional/performance, ergonomic/comfort, and safety/health considerations. The concept generation and selection process are documented, followed by detailed description of the cooling system engineering, garment design principles, material selection criteria, and integration approaches. Then the evaluation methodology that will be applied to assess the system's performance is also discussed.

Chapter 4 provides a comparative analysis of the newly designed WCDS against three commercial cooling garments through thermal manikin testing. The methods section details the clothing ensembles, testing equipment, environmental conditions, and measurement protocols. Results quantify the cooling power, thermal resistance, and evaporative resistance of each system, with analysis of performance differences. The superior cooling capacity of the WCDS is highlighted, demonstrating its potential to reduce heat strain and improve thermal comfort for healthcare workers.

Chapter 5 assesses the effectiveness of the WCDS through human subject testing in simulated healthcare environments. The methods section describes the participants, clothing, protocol, measurements, and statistical analysis used in the study. Results present the physiological responses including core temperature, skin temperature and heart rate, along with microclimate conditions within the protective clothing system. Subjective thermal comfort and usability assessments provide user experience data. The

discussion integrates objective and subjective findings to evaluate the system's practical effectiveness for healthcare workers wearing protective clothing.

Chapter 6 transitions to the design of personal cooling garment for outdoor workers in hot environments. The chapter establishes design considerations specific to outdoor work conditions, including environmental exposure, mobility requirements, and cooling duration needs. The conceptual design process is documented through ideation, comparative technology assessment, and selection criteria for optimal cooling approaches. The detailed design section covers the cold air system engineering, garment configuration, material selection for durability and comfort, and ergonomic considerations specific to outdoor work patterns. The prototype development process and initial testing approach are outlined.

Chapter 7 presents the evaluation of the ventilation cooling garment compared with commercial air cooling garment through sweating thermal manikin testing. The methodology details the test conditions, environmental parameters, and measurement protocols used to assess thermal performance. Results quantify three aspects of the cooling system: cooling power, additional water loss rates, and air outlet temperature which provide reference values for the clothing microclimate cooling potential. This chapter provides essential technical validation of the system's cooling capability and efficiency before proceeding to human subject testing.

Chapter 8 investigates the performance of the ventilation cooling garment through human subject testing during medium-intensity exercise in hot environments. Comprehensive physiological response data including core temperature, mean skin temperature and heart rate are continuously monitored throughout exercise and recovery phases. Subjective assessments using standardized scales evaluate thermal sensation, thermal comfort, thermal preference, perceived exertion, movement restriction, and overall system usability during testing. The wearing trial results establish the practical effectiveness, optimal usage parameters, and limitations of the cooling system for outdoor occupational applications.

The final chapter summarizes the key findings and contributions of the thesis. The conclusions address the effectiveness of the two developed cooling garments, their comparative advantages, and practical considerations. The limitations of current designs are critically assessed, leading to specific suggestions for future research directions, including potential technological refinements, expanded application scenarios, and integration with other protective systems. The chapter aims to provide a research direction for advancing personal cooling solutions across diverse occupational settings.

# Chapter 2 Literature Review

## 2.1 Introduction

Personal cooling garments (PCGs) have emerged as an effective cooling strategy for managing thermal stress and improving performance in thermally challenging work environments [14, 15]. As occupational heat exposure risk continues to increase due to climate change and industrial demands, researchers have increasingly focused on designing, testing, and optimizing various cooling garment technologies to mitigate heat-related strain. Various types of PCSs have been investigated and reviewed in detail [18, 28-30].

This chapter provides a systematic review of the current state-of-the-art in personal cooling garment technology. The literature will be analyzed through the following aspects: 1) Existing PCGs will be classified according to their fundamental cooling techniques; 2) The critical factors affecting cooling effectiveness will be discussed; 3) The specialized PCG designs targeting specific occupational scenarios and user groups will be highlighted; 4) The evaluation methodologies used to assess PCG performance will be compared.

The chapter concludes by summarizing key achievements in PCG research while identifying knowledge gaps and technical challenges that require further investigation.

This analysis aims to provide a comprehensive foundation for understanding current

capabilities and limitations of cooling garment technologies, which is used to guide future innovation in this field.

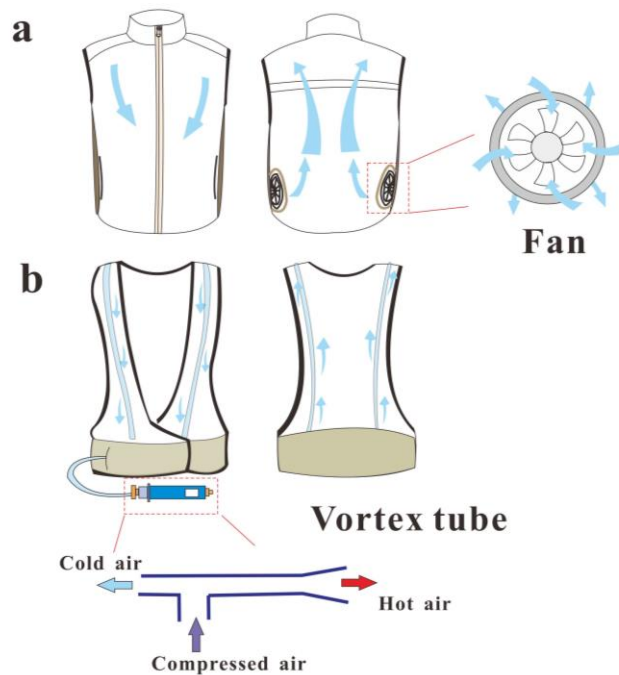
## **2.2 Classification and design parameters of different cooling garments**

Personal cooling garments can be categorized into six different types based on the cooling technique used, namely, air cooling garments, evaporative cooling garments, phase change cooling garments, liquid cooling garments, thermoelectric cooling garments, and radiative cooling garments. Detailed discussions, such as the definition, principle, cooling effectiveness and design factors affecting the effectiveness of each category will be discussed in this chapter.

### **Air cooling garments**

Air cooling garments (ACGs) which improve the convective and evaporative heat dissipation of the human body can be further classified into two types: active and passive ACGs. The active ACGs require batteries or external energy supplies to promote ventilative heat exchange within the clothing microenvironment. A forced convection can be introduced by electronic devices such as fans [31] (Figure 2.1(a)), vortex tubes [32] (Figure 2.1(b)), blowers [33], etc. In terms of garment design, to create sufficient air space between the garment and the human body, the outer layer of most active ACGs is usually made of wind-proof fabric to prevent air from escaping to the environment before sufficient heat exchange. In contrast, passive ACGs rely on air

ventilation triggered by body movements and natural convection as well as the internal characteristics of textiles. The cooling effect can be regulated by the opening and mesh or spacer and mesh structures of a garment [34-37].



**Figure 2.1** The schematic diagram of active air cooling garments (e.g., cooling achieved by fan(a) and vortex tube(b)).

The cooling effectiveness of ACGs can be affected by many factors, such as clothing design, environmental conditions, and the users. From the aspect of clothing design, these factors are related to the clothing size, the type of devices, the placement site of devices, the opening site, and the clothing eyelet. Zhao et al. [38] studied the design of locations for fans and openings at different torso sites. They found that the lower front placement site with both front and back openings achieved the best cooling performance. For the localized cooling, the ventilation location had more influence than the design of the opening. The ventilation units can be placed anywhere requiring more

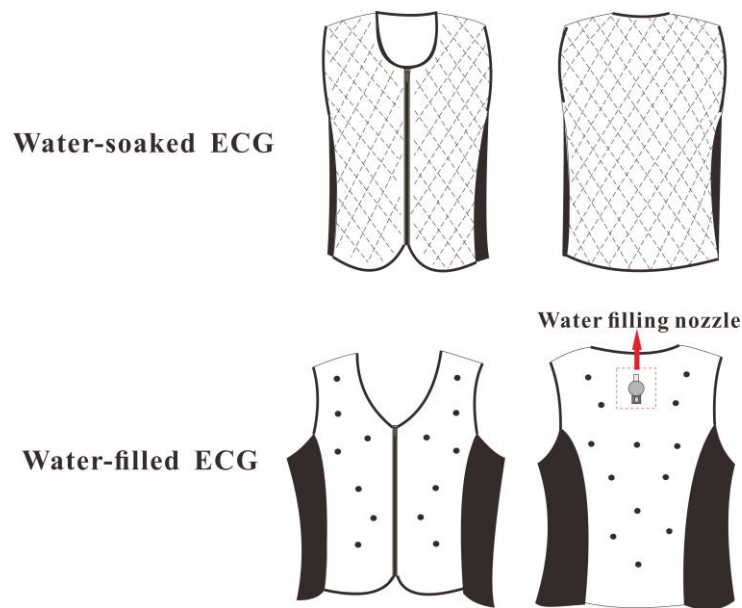
evaporative cooling. The adjustable openings (closed or opened) are helpful for the wearers' comfort but have no significant difference in the cooling performance under the same flow rate. Zhao et al. [39] investigated the effect of clothing eyelet designs (sizes and positions) for the air ventilation system and found that the eyelet could reduce the clothing bulkiness ( $p < 0.05$ ) but had no significant impact on the cooling effectiveness ( $p > 0.05$ ). Ho et al. [34] designed 10 different opening and mesh styles of T-shirts and found that the openings applied at two vertical side panels along the side seams of t-shirts were the most effective to release heat and moisture from the human body. Yang et al. [40] found that the upper body heat loss of ACGs was related to the combined influences of ventilation rate and clothing size. The ventilation rate can increase upper body heat loss, while the clothing size has almost no impact on the effectiveness in high ventilation. Yi et al. [31] evaluated different ventilation units for ACGs and found that ACGs with higher flow rates perform better, which can achieve a higher cooling power. Lou et al. [41] investigated the effects of garment design on cooling performance and recommended that the inner space between ACGs and the human body that may influence the efficiency of heat exchange is important for garment design.

In brief, ACGs provide an innovative approach to enhance thermal comfort and mitigate physiological strain. These cooling garments, which create an air gap between the body and clothing, coupled with active cooling mechanisms such as fans or blowers, offer effective heat dissipation. For the design of active ACGs, the eyelet design and

adjustable openings are helpful for the bulkiness problem caused by the impermeable outer fabric; at the same time, the inner space between ACGs and the human body also needs to be considered in the design process. Placing devices with a higher flow rate at the sweating region is preferred for improving cooling efficiency, while the direct cooling of fans at their location may decrease the localized comfort sensation.

### **Evaporative cooling garments**

Evaporative cooling garments (ECGs) are based on the phase change of liquid (mostly water or sweat generated by the human body) from liquid to vapor state that can absorb heat for personal thermal management. As a passive cooling garment, it is energy-saving and environment-friendly. There are two mainly types of ECGs (Figure 2.2): One is a liquid-soaked (water mainly) garment that provides cooling by direct contact with the skin surface; it should be dipped in liquid to reserve the cooling liquid in the garment before use. Another is dry evaporative cooling garments that need to be filled with water before use.



**Figure 2.2** The schematic diagram of evaporative cooling garments.

The cooling performance of the ECG is related to the properties of the clothing fabric, fitness, and ambient environment, such as the moisture evaporation and water vapor permeability of fabric and the air gap between the human body and clothing. For this type of garment, the cooling only happened on the outer clothing surface, not the inner surface. Hes et al. [42] studied the cooling effect of wet fabric with the fabric worn with or without an air gap between the skin and the fabric. They found that the cooling efficiency increased with the increase of the fabric moisture content without air layers, and if 2 mm and 4 mm thick air layers were involved, the total cooling efficiency would not be influenced by the water content. The better cooling performance happened when the fabric had direct contact with the skin. Guan et al. [43] studied the cooling power of ECGs that provide cooling by sweating from the human body and showed that the evaporative area and locus (in-plane and trans-plane moisture transfer) were determinants of the cooling efficiency. The cooling efficiency was negatively correlated

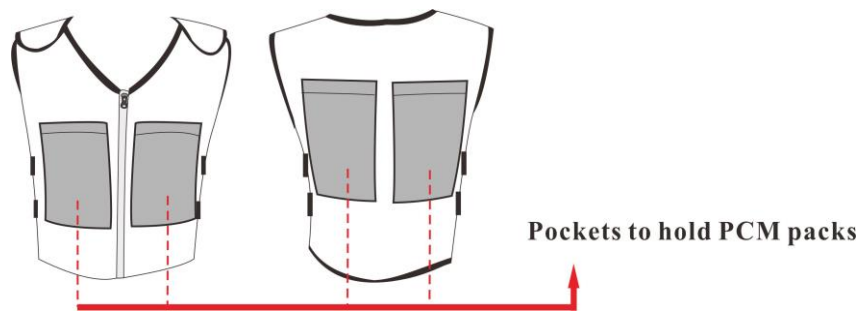
with the evaporative resistance and the thickness of the fabric. Gillis et al. [44] assessed an ECG saturated with combined menthol and ethanol for evaporative cooling performance versus that with water and found that menthol and ethanol caused cooler sensations and a heat storage response.

ECGs utilize the natural phase change of water from liquid to vapor to provide effective personal cooling. They offer an energy-efficient and environmentally friendly approach to maintaining thermal comfort. To improve the cooling performance of ECGs, the first step is to increase the liquid content and ensure that the fabric has direct contact with skin. The second is to decrease the evaporative resistance and thickness of the fabric for ECGs.

### **Phase-change cooling garments**

Phase-change cooling garments (PCCGs) provide cooling through phase-change materials (PCMs) which can store latent heat for thermal energy transfer. PCMs can absorb heat from the body surface during the phase-change process that can increase the heat loss of the human body. PCMs can absorb or release heat at a constant temperature. Over 150 phase-change materials are used in scientific research [45]. Some commonly used PCMs are ice, frozen gel, and paraffin waxes. They have different phase-change temperatures (from 0–40 °C) and can be applied for various heat storage capacities [46]. There are two primary technologies used for the development of PCCGs. One is the phase-change material packs which can be placed inside the

garment's pockets (Figure 2.3). The other is to incorporate PCMs into daily clothing, such as ordinary fabrics or fibers. (1) Phase-change microcapsules are PCMs packaged within a suitable wall material which can be impregnated or coated on the surface of the garment [47, 48]. (2) Phase-change fiber is the PCM packaged inside a fiber that can be used in garment textiles [49, 50]. However, the preparation process of phase-change microcapsules and fiber spinning is complicated and costly, and most studies focus on the development of materials; there are limited studies about the cooling garments that are made by fibers containing phase-change microcapsules.



**Figure 2.3** The schematic diagram of phase-change cooling garments.

The cooling effect of PCCGs mainly depends on the clothing design as well as the form and selection of PCMs. Yoo et al. [51] investigated the effects of the number and position of PCM-treated fabrics and found that the treated fabric with a greater amount of PCMs performed better. Moreover, if there is more than one layer, the outer layer of the garment is more appropriate for the effects of the PCMs. According to Mokhtari et al. [16], the PCM microcapsules can only provide a small capacity of heat absorption (about 15 W) with the limitation of the weight of materials that can be coated on the garment. Hence, they are not applicable in hot environments, where ice packs are more

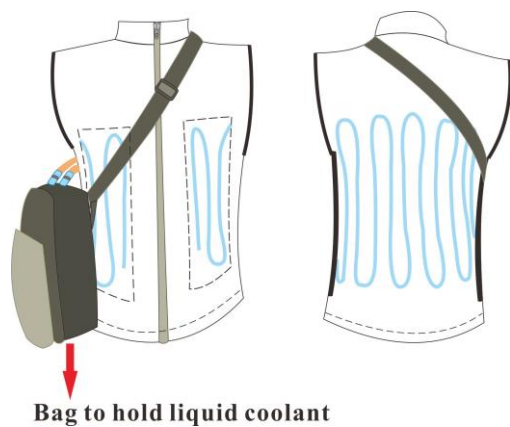
effective. House et al. [52] assessed the performance of four PCCGs containing different PCMs, which melted at 0 °C, 10 °C, 20 °C, and 30 °C separately, and the PCCGs were worn under firefighters' protective clothing. They found that 10 °C has the best cooling efficiency when combining work and rest periods, and they also stated that a cooling vest containing ice packs (melting at 0 °C) could be used only if the thermal resistance between the ice packs and the skin was higher. Gao et al. [53] evaluated PCCGs with different melting temperatures, masses, and covering areas and found that the PCCG with the lower melting temperature (24 °C) performed better than those with higher melting temperatures. They also found that the cooling performance was mainly determined by the covering area, while the cooling duration depended on the PCM mass. In hot climates, the temperature gradient for PCCGs was suggested to be equal to or greater than 6 °C.

PCCGs represent an innovative and promising solution for achieving effective cooling and enhancing thermal comfort in various environments. By harnessing the properties of PCMs that can change from solid to liquid and vice versa to create a cooling effect, these garments offer a unique approach to regulating body temperature. The design and composition of PCCGs play an important role in their cooling efficiency. A higher mass of PCMs or PCM microcapsules is positive for cooling efficiency, and the lower melting temperature can provide a higher cooling rate. The higher phase-transition temperature can provide a longer cooling duration. A temperature gradient over 6 °C is recommended. Ice packs can only be used when there is sufficient thermal resistance

between the skin and ice. At the same time, the covering area needs to be considered in the design of PCCGs.

### **Liquid cooling garments**

Liquid cooling garments (LCGs) provide cooling by the pump-driven circulation of liquid coolant inside the tubes embedded in the garment (Figure 2.4). The tubes may be sewn into the fabric layer, and the pump is powered by electricity. The circulating liquid may be cold or icy water, liquid metal, or a mixture of water and propylene or ethylene glycol [54, 55]. The liquid microclimate cooling systems produce a temperature gradient that makes the conductive and convective heat transfer take place among the coolant, the human body, and the environment.



**Figure 2.4** The schematic diagram of liquid cooling garments.

The cooling performance of LCGs depends on the design of the clothing, the ambient condition, and the controller, which determines the liquid flow rate, coolant temperature, and intermittent or regional cooling control [56-60]. In terms of clothing design, it is related to the fitness, tubing characteristics, different body areas, and fabric [61-64]. Kayacan et al. [57] compared two different designed LCGs and found that the fabrics

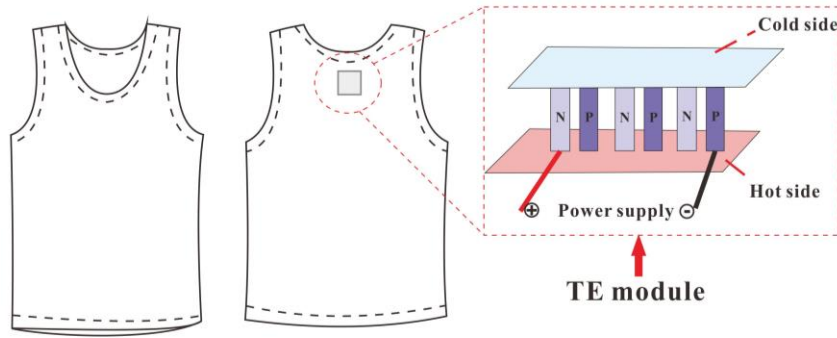
with a natural curved structure performed better than the plain fabrics; they also found that when the liquid inlet temperature was decreased, the effective cooling increased slightly. Burton et al. [58] found that the heat removal rate of LCGs was not linearly related to the flow rate when the flow was relatively slow. When the flow rate exceeds 1 L/min, little further improvement in the cooling performance can be made with the increase in flow rate. These findings were also shown by Frim et al. [56]. Dionne et al. [65] evaluated PCGs with different densities of tubing through thermal manikin testing. They found that under the condition of the same flow rate and liquid inlet temperature, the heat removal rate increased with the density of the tubing. Branson et al. [61] used a 3D body scanner to study the effect of fitting of LCGs and concluded that from the aspect of different users, it was better to develop an adjustable cooling garment. Cao et al. [64] investigated the effect of inner fabric layers of LCGs on heat exchange and cooling efficiency. They found that an inner layer with good thermal conductivity, good moisture management, and good tactile properties was desirable.

LCGs offer a promising approach to regulating body temperature and enhancing comfort. These garments utilize the circulation of cold liquid through tubes in clothing to facilitate heat exchange between the body, the liquid, and the environment. For the design of LCGs, a lower liquid temperature with a higher flow rate (no more than 1 L/min) is beneficial to improve cooling performance. As conductive heat transfer is the primary cooling mechanism for LCGs, a good fitness of LCGs can also increase cooling efficiency. An adjustable (fitness and flows) LCG could be designed to reduce

the discomfort caused by the coolant having direct contact with skin, and a three-layer system may be better for wearer comfort. The comparative analysis of different LCGs demonstrates their varied cooling powers, durations, and temperature ranges, allowing for tailored choices based on specific cooling needs. Further exploration and real-world studies will contribute to a deeper understanding of LCGs' performance and their utility in diverse settings.

### **Thermoelectric cooling garments**

Thermoelectric cooling garments (TCGs) are based on the Peltier effect that can convert electrical energy into thermal power. The single-stage thermoelectric (TE) module is composed of type-N and type-P semiconductors which connected electrically in series. The Peltier effect can transfer heat from one side to the other; therefore, one face is heated and the opposite is cooled, which can be changed by the direction of the electric current [66, 67]. A single TE device can be embedded in a clothing system to provide cooling by direct contact with the skin [68] (Figure 2.5). However, there are some apparent weaknesses in the design of such TCGs, for example, the poor coefficient of performance and low efficiency, so there is nearly no cooling garment designed solely using the Peltier effect. Some enhanced cooling garments, such as the combination of the air and TE cooling techniques which enhance air cooling through the TE unit [20, 69] and the combination of the liquid and TE cooling techniques which enhance liquid cooling through the TE unit [69] were developed for better cooling performance.



**Figure 2.5** The schematic diagram of thermoelectric cooling garments.

### **Radiative cooling garments**

Radiative cooling garments (RCGs) provide thermal comfort through enhanced radiative heat loss from the human skin or the clothing outer surface. Human skin can be regarded as a near-black radiating source with an emissivity value over 0.95 [70, 71], which makes it a near-perfect emitter of thermal infrared radiation. Based on this concept, some fabrics, textiles, and garments were designed for personal thermal management. The cooling garment with mid-IR transparency [72], mid-IR emissivity [73], or solar-reflecting mid-IR emissivity [74] are all potential solutions to achieve better cooling efficiency. RCGs as passive cooling systems contribute to energy saving. The innovation of RCGs mainly focuses on the material design [75-78]; there is limited knowledge about the cooling performance of this kind of garment which may need more attention.

## **2.3 Comparison of different types of cooling garments.**

Table 2.1 offers a comparative analysis of four different types of PCGs based on various

parameters including cooling power, weight, duration, testing scenario, cooling area, and cooling temperature. The results show that the cooling powers of the different PCGs range from 6 to 340.4 W. The enhanced LCG which is based on thermoelectric refrigeration demonstrates the highest cooling power, while the PCCG exhibits the lowest. The estimated cooling power for ACGs, PCCGs, LCGs, and ECGs ranges from 15.5 to 106 W, 6–98.6 W, 67.2–340.4 W, and 48–57 W, respectively. Weight is an important consideration for portable cooling systems, and lighter systems are usually preferred [79]. The weight of the personal cooling garments listed in this table varies from less than 100 g to over 3000 g, and ACGs present a relatively lower weight among these cooling garments. The testing scenarios, including temperature, humidity, and air velocity, listed in the table are important for the evaluation and application of different cooling systems. Most cooling garments are designed for use in hot climates which are higher than 30 °C, and the recommended temperature gradient for PCCGs is suggested to be greater than 6 °C.

The duration of cooling is an important consideration when choosing a cooling system for a particular application. The duration of cooling provided by each cooling technique ranges from less than an hour to several hours. For active ACGs, the cooling duration is dependent on the battery provided for the cooling unit. For PCCGs, it is related to the weight, covering area, and cooling temperature of the PCM. For LCGs, it is influenced by the flow rate, weight, and temperature of the cooling liquid.

Additionally, the cooling area is more important for designers to achieve better cooling performance. The cooling temperature for active ACGs is related to the environmental temperature and cannot be fully controlled by users; PCCGs and LCGs' cooling temperature is related to the phase-transition temperature of the PCMs and the temperature of the cooling liquid, respectively, and both cannot be fully controlled by the user; and for ECGs, water evaporation is highly wind-speed dependent.

**Table 2.1** Comparative analysis for different types of personal cooling garments.

Ref	Cooling Technique	Cooling Power(W)	Weight	Duration	Testing Scenario	Cooling Area	Cooling Temperature
[38]	ACG	71.5–106	N/A	N/A	34 °C, 60% RH, 0.4 m/s	N/A	N/A
[80]		79.5–97.6	N/A	N/A	30–34 °C, 90% RH	0.53 m <sup>2</sup>	30 °C
[31]		67.72 ± 0.74	98g (Fan only)	7.05 h	34 °C, 60% RH, 0.4 ± 0.1 m/s	N/A	N/A
[20]		15.5	994 g	N/A	26.1 °C, 50% RH	N/A	19.8–26.5 °C
[81]		51.7	1.2 kg	N/A	23 °C, 50% RH	N/A	N/A
[53]	PCCG	19.2–28.4	2224 g	2.5 h	Hot climates (the required temperature gradient is suggested to be greater than 6 °C)	0.2054 m <sup>2</sup>	≥24 °C
		12.9–21.2	2226 g	4.8 h			≥28 °C
		6.0–14.2	1973 g	6 h			≥32 °C
		[82]	8.4	1296 g	65 min	30 ± 0.5 °C,	0.1404

		10.5		125 min	80 ± 5% RH, <0.1m/s	m <sup>2</sup>	≥15 °C
[83]		10–20	2224 g	210 min	34 ± 0.5 °C, 60% RH, 0.4 m/s	0.57 m <sup>2</sup>	≥21 °C
[21]		89.6 ± 9	3400 g	N/A	37 °C, 50% RH	0.4 m <sup>2</sup>	N/A
[17]		13.4–19.4	1800 g	≥2 h	30 °C, 45% RH	N/A	N/A
[84]		67.2–138.1	1500 g	0.79–3.36 h	40 °C–50 °C	0.568 m <sup>2</sup>	N/A
[85]	LCG	300 W	<10 kg	≥1 h	30–45 °C, 20–80% RH	N/A	22–27 °C
[86]		90.8–96.5	3000 g	90 min	35.89 ± 1.25 °C, 35% RH		10–15 °C
[69]		340.4	N/A	N/A	30 °C		≥15.7 °C
[87]		ECG	48–57	N/A	N/A		40 °C, 10% RH

## 2.4 Applications and design of cooling garments

Some cooling protocols have been designed based on the application scenarios to reduce heat strain for human subjects under different working conditions.

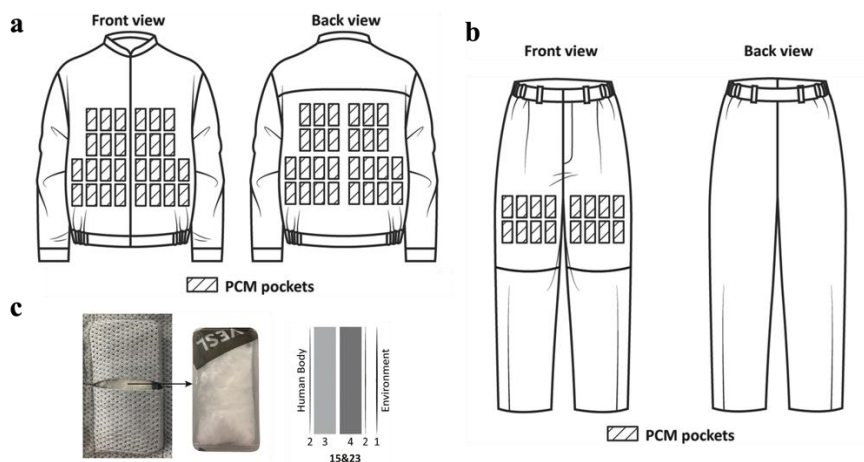
### Miners

Miners always work in deep and ultra-deep mining environments that are hot and humid.

The increase of temperature (10 °C per km of depth) and humidity (that can easily reach

over 80%) [88] can cause heat stress which is negative to the physical health and safety of workers. Some existing commercialized personal cooling garments are not so compatible with the reality of deep mining conditions [89]. Therefore, new personal cooling garments designed for miners are necessary to assist the human body in evacuating excess heat with artificial cooling technique, which will lead to better working condition.

Zheng et al. [82] designed a cooling garment ensemble (long-sleeved jacket and trousers) for miners with 72-mesh liner pockets that holds different phase change materials (PCMs)(15 °C PCMs as the inner layer and 23 °C PCMs as the outer layer), total 144 PCM packs (two packs overlapped in one pocket) are inserted into the garment. The total coverage area of PCM packs is 1404 cm<sup>2</sup>.



**Figure 2.6** Schematic diagram of the cooling garment(a,b), a pocket with two PCM packs inserted and structural layer of two PCM packs arrangements(c). [82]

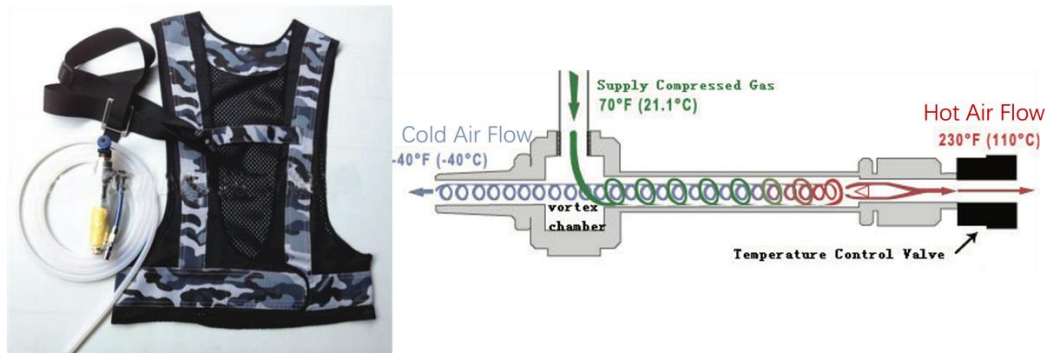
Al Sayed et al. [33] developed an Air/CO<sub>2</sub> cooling garment for miners, which consists

of three parts, including the garment layer (the outside layer, the middle layer and the inside layer), the air treatment system, and the distribution channels (Fig 2.7). The ATS used the two-phase(liquid/gas) CO<sub>2</sub> that contained in two cylinders to cool and dehumidify the air taken from the surroundings. The system is attached to the back side by pockets with straps and fastening ribbons. Battery was placed in the pockets to power the fan. PVC tubes were used as distribution channels with different diameters varied between 4.5 and 8 mm, and a total of 20 holes were equally distributed throughout the garment (the front and back).



**Figure 2.7** Front and back view and the air treatment system of the Air/CO<sub>2</sub> cooling garment.[33]

Zhai et al. [32] developed a mine cooling garment with the vortex tube type. The vortex tube was operated by the compressed air and the filtered compressed air was separated into two parts with different temperature, the hot air flowed out and the cold air was delivered to the trunk of the human body through the hole of the cooling garment. The airflow guide was evenly distributed on the vest and there was a manual knob to control and adjust the outlet air temperature.

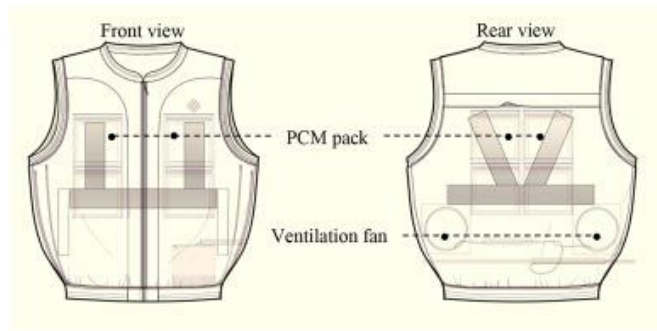


**Figure 2.8** Vortex tube cooling garment and the schematic diagram of air flow in vortex tube.[32]

## Construction workers

Construction workers that perform strenuous physical work and have direct exposure to the sun are vulnerable to heat stress [8]. Some cooling modalities such as pre-cooling, continuous cooling and post-cooling have been applied in working sites [90, 91], but not so practical in outdoor working scenarios.

Yi et al. [92] developed a hybrid cooling garment for construction workers. It incorporated eight PCM packs (melting temperature:28 °C) placed evenly on the front (4) and back (4) areas and a pair of detachable ventilation fans powered by a battery on the lower back area (Fig 2.9). The cooling garment had three modes, including PCMs with Fan-on, PCMs with Fan-off, and Fan-on only.



**Figure 2.9** The geometric picture of the cooling vest that designed for construction workers.[92]

### **Iron foundry workers**

Iron foundry workers that work in the foundry near the core furnace and melting area are exposed to high heat and radiation. Meanwhile, the heavy physical works and poor working environment also contribute the heat stress which increases the health risks and decreases work efficiency [93]. Some cooling garments have demonstrated considerable heat reduction capabilities [53, 94].

Shirish et al. [86] reported a cooling system which is a simple vest with silicone rubber tubing inside, covering about 30% of body(Fig 2.10). The liquid ice-chilled coolant was circulated in the tubing system which placed on the trunk and back area. There was a backpack for an ice-water reservoir, a small pump and a rechargeable battery pack. The Velcro straps were used in the garment to fit any person.



**Figure 2.10** Front view and side view of Personal cooling garment with silicon tubing.

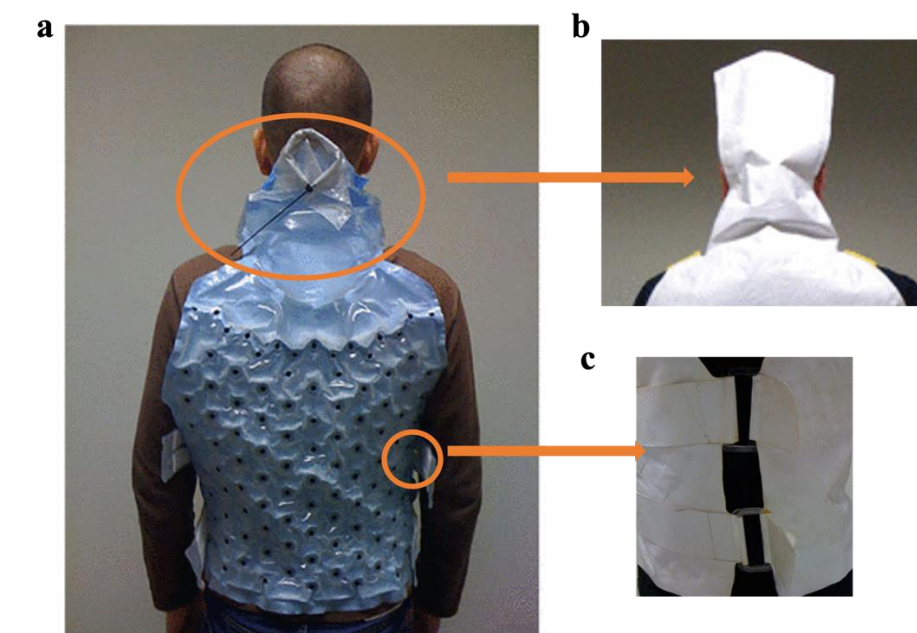
[86]

## **Firefighters**

Cooling is a feasible option for firefighters to deal with occupational heat. Occupational firefighters often work under extremely hot conditions (from 100 °C to 30 °C) [95]. The encapsulated firefighters' protective clothing which raises body temperature may lead to uncompensated heat loading and the metabolic heat caused by strenuous work poses serious safety issues, especially the injuries from heat exhaustion [96-98]. The personal cooling garment is deemed to be an effective option to help normalize body temperature [99, 100].

Roderick et al. [101] developed a quilted plastic cooling vest for firefighters in the bush of rural Australia. The garment consisted of two layers, Polyethylene and Polypropylene, which were welded together during production. The cooling vest could be activated by pouring water into the collar section (Fig 2.11.a) through a large filling orifice (Fig 2.11.b) that could be rolled up and sealed. It had side buckle or velcro

fastening straps (Fig 2.11.c) for fitting. When the chemical (the urea granules) contained in the vest mixed with water, the fluid inside cools itself to approximately 5 °C. The shape of the hole pattern governs the flow rate of chilled water. It is a single use product but can be recycled appropriately.



**Figure 2.11** Back view and side view of Personal cooling garment.[101]

## Medical personnel

The environmental condition of hospital operating room should be adapted to the patient's comfort requirements during a surgical procedure [102]. Nevertheless, medical personnel such as surgeons, nurses and anesthesiologists have different thermal comfort sensations in the operating room [103-105]. It is almost impossible to set a temperature comfortable for all persons. For this reason, personal cooling garments were proposed to increase thermal comfort in their working site.

Langø et al. [106] designed a cooling vest for surgeons using PCM elements. (Fig 2.12). The clinical and laboratory tests were carried out for an iterative design process. A permeable, thin material was used, and the PCM used in this study had a melting point of 28°C. The final designed vest was adjustable for different body sizes, which was beneficial for the surgeon's movement. The PCMs were configured with small spaces between, which was useful for sweating transport, also easy for inserting and removing PCMs. An additional synthetic fiber shirt with silver fibers under the vest was designed to ensure the heat and moisture transportation.



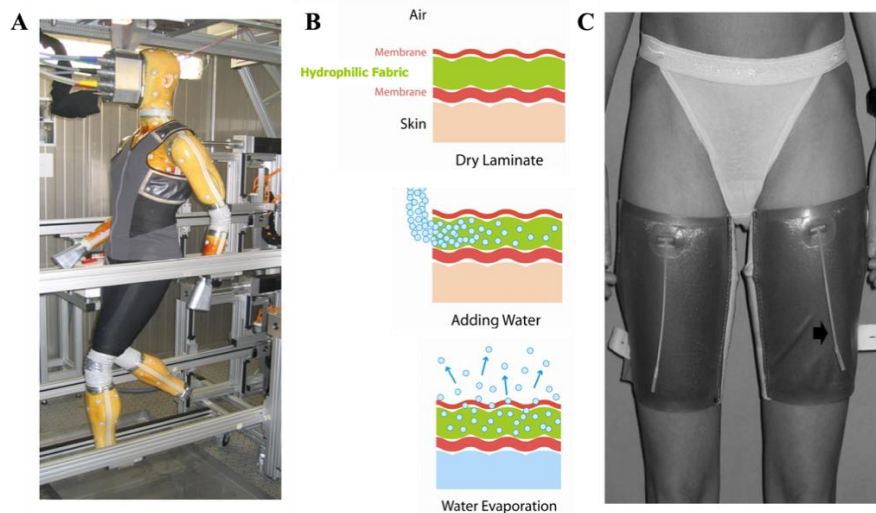
**Figure 2.12** A medical personnel cooling vest. View from back (a), front view (b), and cooling elements inside vest (c).[106]

## Patients

Cooling processes have been applied in medicine for many years. Personal cooling garments was proposed as a beneficial and convenient method to induce hypothermia (or avoid hyperthermia). Heat sensitivity is a peculiar feature of multiple sclerosis (MS) patients [107]. It is estimated that 60–80% of MS patients present temporary worsening

of clinical symptoms when their body temperature increases [108, 109]. There are studies show that personal cooling has positive effects which can maintain body temperature and provide temporary symptoms relief for MS patients [110, 111].

Kocjan et al. [112] proposed a lightweight portable prototype cooling garment for MS patients, which is a three-layer laminate structure. Water was added into a hydrophilic fabric that placed between two water vapour permeable membranes (Fig 2.13). The evaporation of water through the outer membrane increased heat loss from the skin surface. Meyer-Heim et al. [113] designed an improved thigh-cuff cooling garments based on the textile multilayer laminate, which also operated on the principle of water evaporation. The cuff consisted of two separate chambers and included tubes for filling water and fastener to adjust fitness.



**Figure 2.13** The clothing ensemble(A) manufactured from the prototype cooling garment and its functional properties(B). Thigh-cuff cooling garments(C).[112]

## Athletes

Many athletes exercise in the hot and humid environment (i.e., 30–35°C, 60+% relative humidity (RH)) which affect exercise performance and increase the risk of heat-related illness [114-116]. Pre-cooling before exercise (i.e., PCM) [117] and continuous cooling during exercise (i.e., New designed sportswear) have been developed to provide cooling comfort for sports people.

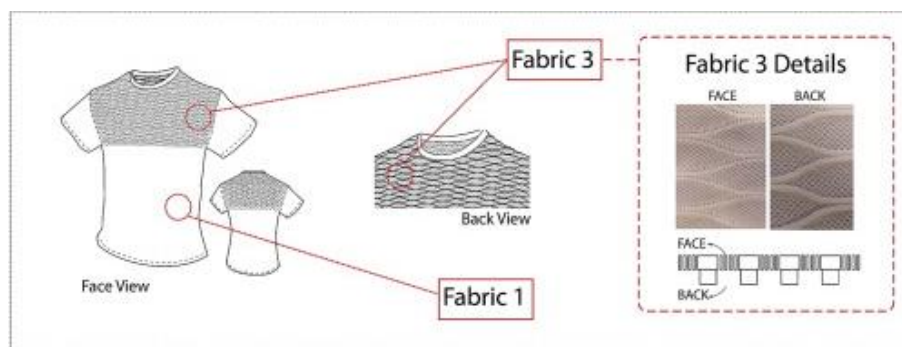
Some open construction has been applied in sportswear to increase body ventilation and release heat and moisture from body [118, 119]. Ho et al. [119] developed a series of plain jersey t-shirt with different types and positions of openings (6 pieces for mesh style and 3 pieces for opening style) (Fig.2.14). They found that the design of vertical side mesh panels of t-shirt was better for ventilative cooling.



**Figure 2.14** Mesh style: Mesh area was placed across the front and back chest horizontally. Mesh area was placed at the center front and back. Two vertical side mesh panels were placed along the side seams and armhole area. Opening style: Opening was

placed across the front chest and back. Openings were placed at the side seams. [119]

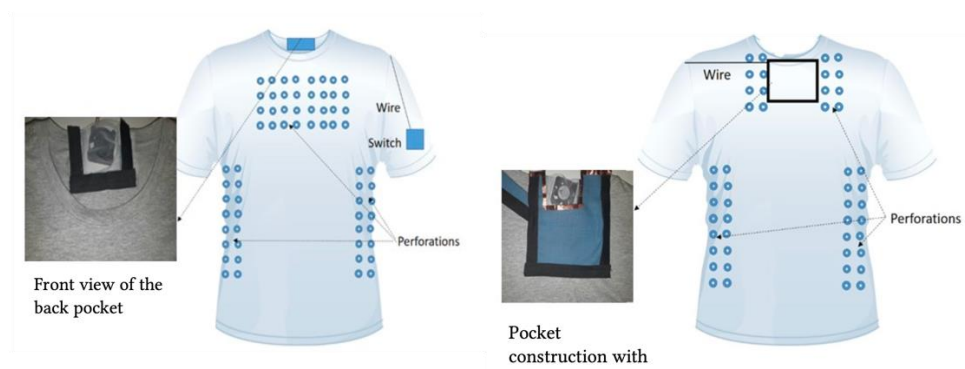
Based on the opening design of T-shirt, Sun et al. [35] designed a novel T-shirt which combined the spacer and mesh structure (Fig 2.15). The spacer structure was created by float on a single needle. And the mesh opening that made by elastic yarns was created by float plating technique. The spacer fabric at the chest and back area was used to prop the garment up, which reduced the discomfort caused by heavy sweating and improve air flow between the fabric and human skin.



**Figure 2.15** T-shirt with spacer and mesh structure.[35]

Wickramaratne et al. [120] recruited 20 endurance cycling athletes to brainstorm the sports cooling comfort requirements and ideas for the design of cooling sportswear. After analyzing the group transcripts, they designed three prototypes including Peltier and fan cooling with manual control (Fig 2.16), automatic cooling with a PC fan to fulfil all the cooling requirements. The Peltier cooling and fan cooling were both controlled by a switch placed on the sleeve of the sportswear. The automatic cooling garment was controlled by a smart phone based on the upper back temperature provided by a temperature sensor.

These designs have perforated material insertions in underarm and chest areas which matched the body sweating zones to promote sweat evaporation, and the open construction was built on the upper back area to promote cooling effect. All the cooling unit was placed in a simple pocket construction. The entire cooling unit, wire and switch are detachable, so the sportswear can be laundered like normal clothes.



**Figure 2.16** Front and back side of the prototype.[120]

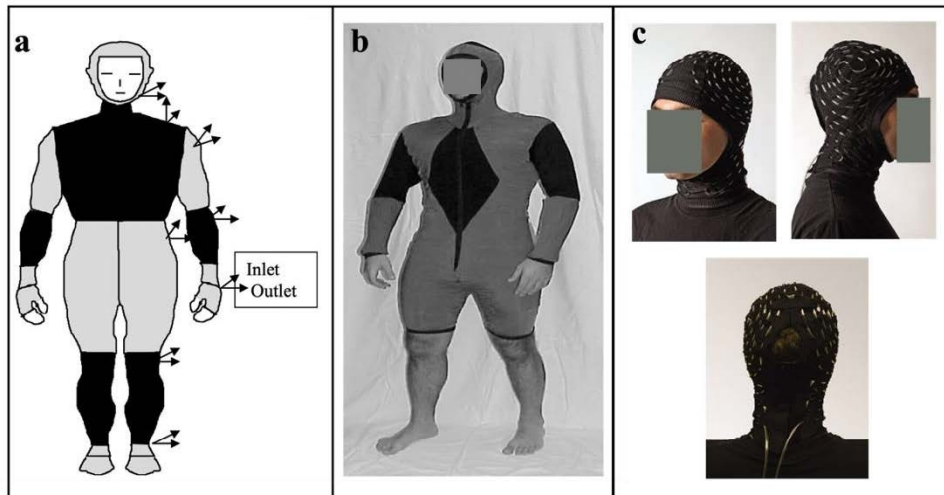
## **Astronauts**

Liquid cooling garment (LCG) is important for the space suit during the extravehicular activity (EVA) [121]. The extravehicular suit pressurized to protect the human body lowers the mobility. The hard exercise during EVA generates heat enclosed in the insulated suit. Both the immobility and heat create discomfort to the astronaut [122, 123]. The LCG is proved to be an effective strategy for regulating body heat for astronauts.

The National Aeronautics and Space developed a multicompartment liquid cooling/warming garment, named the MACS-Delphi for astronauts [124, 125]. The

garment was divided into eight body zones for manipulating the temperature on different body parts (Fig 2.17.a). The tubing system was sewn onto a cotton/lycra fabric. After this, a shortened garment with less body surface coverage was designed which consumed less energy (Fig 2.17.b).

Then they collaborated with Kim et al. [121] to improve the MACS-Delphi hood (Fig 2.17.c) which is the beginning step for the MACS-Delphi improvement. The mesh structure of the fabric for the hood had 1/8-inch-wide openings, being large enough for the tubing to go through. These openings spaced every 1/8 inch in both the warp and weft directions that can be stretched adequately. Tubes can be inserted easily and be fixed firmly. The tube length of the new designed hood was 6.23 m. The Velcro™ tape at the back neck was adjustable to accommodate different head sizes. And the opening at the top was useful for a person with long hair to pull the hair out. The horizontal tube placement which allowed the tube to move with the fabric stretches and the rib knit fabric provided more flexible body movement for users.



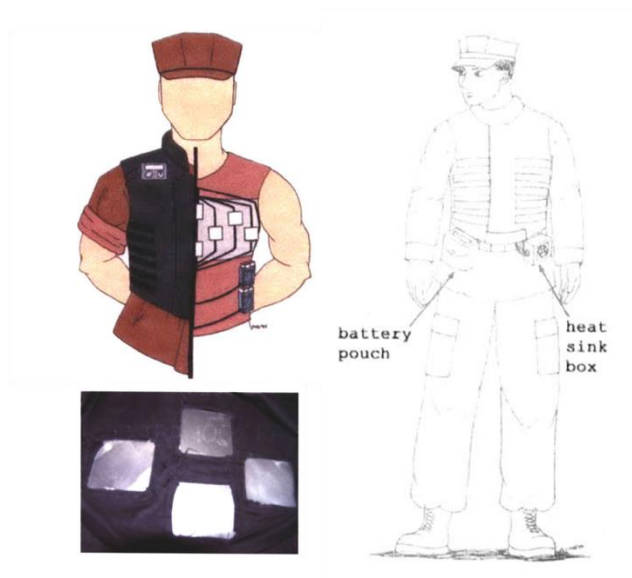
**Figure 2.17** Schematic of the multi-compartment garment design(a), the shortened liquid cooling/warming garment(b) and the new design of the MACS-Delphi hood(c).[121, 124, 125]

## Soldiers

Soldiers' operational and training exercises in hot environments with protective garments or equipment such as body armor and helmets can inhibit the evaporation of sweat which can restrict body heat loss. Without sufficient heat dissipation, individuals may experience considerable heat stress that affect task performance on operations and increase the risk of exertional heat illness [126-133]. To mitigate these problems, personal cooling garments have been developed in different military occupational scenarios.

Gentile et al. [134] designed a novel PCG for soldiers in hot climate. It consisted of a base vest, a thermoelectric (TE) unit, the heat pipes and battery. The TE unit was a 'plug and play' unit which was placed on the front of the vest (elastic pouch). A neoprene chest pad was placed over the TE units for wearers' comfort, and several holes on the

vest to contact the TE unit pad with body. There were also a restraint loop and Velcro tabs to fix the TE unit and keep it close to the body. The heat pipes were inserted into the TE units and it was used as a single bundle, the damaged heat pipe bundle could be repaired and refurbished. A second layer fabric was used to hide all the inner workings, also protected the vest from serious use. The loop and the heat sink block both could be reclaimed for recycling.



**Figure 2.18** A cutaway view of the vest, battery pouch and heat sink box clipped to the belt, the holes in the fabric layer [134].

## 2.5 Evaluation of cooling garments

Several methods have been employed to evaluate PCGs. Thermal manikin tests, human trials and model simulation were the three mainly used methods for the assessment of PCGs [22].

## **Thermal manikin tests**

Thermal manikins are now the most useful tools for assessing comfort-related thermal and evaporative properties of overall clothing systems. Thermal manikins have been investigated for more than 70 years and there are over 100 thermal manikins developed all over the world. It served as a reliable and accurate instrument to analyze and evaluate the thermal factors between ambient environment and human body. Large variations may exist between different type of manikins, and international standards have been developed to accommodate sources of variation [135, 136]. According to ASTM F2371, a sweating heated manikin which can provide objective and repeatable results is a convenient tool to assess the effectiveness of PCGs. “Newton” and “Walter” are two mainly used thermal manikins.

Newton was manufactured in the United States, which is made of carbon-epoxy thermally conductive shell with embedded heating and sensor elements. Newton is fully jointed and divided into many segments, which could provide motion at each joint and allow various possible body postures and control the skin temperature and heat flux independently. There is a removable fabric skin layer designed for sweating system to measure the evaporative resistance of clothing. The amount of water can be controlled through ThermDAC software. Newton has an advanced CAD digital modelling the system was complied with ISO and ASTM standards.

Walter [137, 138] was invented in Hong Kong, which is made of waterproof and vapor

permeable fabrics with a water circulation system, manikin walking system and data recording system. Walter is a one segment manikin, it simulates insensible sweating through the Gore-Tex fabric. There are four pumps inside the manikin, the body temperature was controlled by pumping the heated water from its center to the whole body, and the mean skin temperature can be adjusted through the pumping rate. The joints between the thighs and the body are controlled by a four-bar crank mechanism which can simulate 'walking' motion with an adjustable speed from 0 m/s to 2.7 km/h.

All the manikin tests were carried out in the climatic chamber to simulate a real application scenario and provide a relatively stable environmental condition. The 34-segment manikin Newton and Walter are two mainly used manikin to assess the cooling performance of PCGs. Cooling power is calculated as a difference between the power input to the manikin using the cooling garment and the baseline value under the control condition.

For Walter, the thermal insulation ( $R_{ct}$ ) of the garment is calculated using the following formula:

$$R_{ct} = A_s(T_S - T_a) / (H_s + H_p - H_e - H_a)$$

where  $R_{ct}$  is the thermal insulation of the garment ( $^{\circ}\text{C m}^2 \text{ W}^{-1}$ );  $A_s$  is the total surface area of the manikin ( $\text{m}^2$ );  $T_S$  is the mean skin temperature of manikin ( $^{\circ}\text{C}$ );  $T_e$  is the mean temperature of the environment ( $^{\circ}\text{C}$ ); and  $H_s$  is the power consumed by heaters (W);  $H_p$  is the power consumed by pumps (W);  $H_e$  is the evaporative heat loss from the

skin to the environment (W);  $H_a$  is the power consumed for heating the supplied water to the manikin body temperature.

The evaporative resistance (Ret) was calculated by

$$R_{et} = \frac{A_s(P_{ss} - P_{as}RH_a)}{H_e} - R_{es}$$

$$H_e = \lambda Q$$

where  $R_{et}$  is the evaporative resistance of the clothing ( $\text{Pa m}^2 \text{ W}^{-1}$ );  $A_s$  is the surface area of the manikin ( $\text{m}^2$ );  $P_{ss}$  is the saturated vapour pressure at the skin temperature (Pa);  $P_{as}$  is the saturated vapour pressure at the ambient temperature (Pa) and  $RH_a$  is the ambient relative humidity (%);  $R_{es}$  is the moisture vapour resistance of the manikin skin which was calibrated in advance ( $R_{es} = 8.6 \text{ m}^2 \text{ Pa W}^{-1}$ );  $H_e$  is the evaporative heat loss (W);  $\lambda$  is the heat of evaporation of water at the skin temperature ( $\lambda = 0.67 \text{ W h g}^{-1}$ ); and  $Q$  is the rate of perspiration per hour from the manikin ( $\text{g h}^{-1}$ ).

## **Human trials**

### **Thermo-physiological measurements**

Thermal manikins as the useful tool to assess PCGs still have some limitations as they cannot fully simulate realistic thermophysiological responses, such as the changes of sweat and heart rate. Human subject tests can be conducted independently or combined with thermal manikin to evaluate the PCGs. Human testing provides accurate data for physiological impact of PCGs on the human body with the occupational work intensity and specific test conditions. Normally, Volunteers selected as test subjects should be in

good health to ensure that they could complete the activity and thermal stress required by this study. Other test-specific criteria, such as the use of alcohol, coffee, or medications that could change their thermoregulatory responses should also be considered. Some basic information will be recorded for all participants, including age, height, weight, body surface area, BMI and basic metabolic rate. Before they start the test, a signed consent form is required. The clothing test condition that uses human participants may be limited by scientific or ethical reasons which must be detailed in the test protocol. Parameters such as local and mean skin temperature, heart rate, sweat rate, and core temperature are recorded in human trials for assessing the performance of cooling garments.

The core temperature as an important parameter for thermal strain measurement can be detected directly through a temperature probe or ingestible core temperature pill. Other parameters, such as mean skin temperature ( $T_{skin}$ ), torso skin temperature ( $T_{torso}$ ), mean body temperature ( $T_b$ ) can be calculated using some accepted weighting formulas.

Zheng et al. [82] calculated the mean skin temperature ( $T_{skin}$ ), torso skin temperature ( $T_{torso}$ ) using Equations:

$$T_{skin} = 0.07 * T_{forehead} + 0.175 * T_{scapular} + 0.175 * T_{chest} + 0.07 * T_{upper arm} \\ + 0.07 * T_{forearm} + 0.05 * T_{hand} + 0.19 * T_{thigh} + 0.2 * T_{calf}$$

$$T_{torso} = 0.25 * T_{chest} + 0.25 * T_{abdomen} + 0.25 * T_{scapular} + 0.25 * T_{lower back}$$

where  $T_{forehead}$ ,  $T_{scapular}$ ,  $T_{chest}$ ,  $T_{upper arm}$ ,  $T_{forearm}$ ,  $T_{hand}$ ,  $T_{thigh}$ ,  $T_{calf}$ ,  $T_{abdomen}$

and  $T_{\text{lower back}}$  = local skin temperature ( $^{\circ}\text{C}$ ) at the forehead, scapular, chest, upper arm, forearm, hand, thigh, calf, abdomen and lower back, respectively.

Yi et al. [92] calculated the mean skin temperature, mean body temperature ( $T_b$ ) according to Equations, respectively:

$$T_{\text{skin}} = 0.3(T_{\text{chest}} + T_{\text{forearm}}) + 0.2(T_{\text{thigh}} + T_{\text{calf}})$$

$$T_b = 0.65T_c + 0.35T_{\text{sk}}$$

Where 0.97 is the specific heat of the body (in  $\text{W}\cdot\text{h kg}^{-1}\text{C}^{-1}$ ),  $m$  is the body mass (in kg).

Shirish et al. [86] obtained the weighted skin temperature using the following equation:

$$\begin{aligned} WT_{\text{skin}} = & 0.095 \text{ head}T_{\text{skin}} + 0.255 \text{ trunk}T_{\text{skin}} + 0.245 \text{ back}T_{\text{skin}} \\ & + 0.125 \text{ upper arm}T_{\text{skin}} + 0.035 \text{ hand } T_{\text{skin}} + 0.205 \text{ thigh}T_{\text{skin}} \\ & + 0.04 \text{ foot}T_{\text{skin}} \end{aligned}$$

where  $WT_{\text{sk}}$  = weighted skin temperature

Aljaroudi [139] used the following formula for calculating the mean skin temperature,

$$T_{\text{skin}} = [0.3(T_{\text{chest}} + T_{\text{shoulder}})] + [0.2(T_{\text{thigh}} + T_{\text{calf}})]$$

Except for the core and skin temperature, sweat rate, heat storage also can be calculated through formulas.

Zheng et al. [82] calculated the total sweat production ( $SW_p$ ) and the total sweat evaporation ( $SW_{\text{evap}}$ ) using Equations:

$$SW_p = W_{\text{nude},0} - W_{\text{nude},\text{post-trial}}$$

$$SW_{\text{evap}} = W_{\text{clothed},0} - W_{\text{clothed},\text{post-trial}}$$

where  $W_{\text{nude},0}$  and  $W_{\text{nude},\text{post-trial}}$  = nude body weight before and after the trials, respectively;  $W_{\text{clothed},0}$  and  $W_{\text{clothed},\text{post-trial}}$  = clothed body weight before and after the trials, respectively.

Yi et al. [92] calculated the rate of body heat storage ( $\Delta S$ ) according to Equations, respectively:

$$\Delta S \left( \frac{W}{m^2} \right) = \left[ (0.97 \cdot m) \cdot \left( \frac{\Delta T_b}{\Delta t} \right) \right] / A_D$$

Where 0.97 is the specific heat of the body (in  $W \cdot h \text{ kg}^{-1} \text{ } ^\circ\text{C}^{-1}$ ),  $m$  is the body mass (in kg),  $A_D$  is the body surface area (in  $m^2$ ),  $\frac{\Delta T_b}{\Delta t}$  is the change in TB over time (in  $^\circ\text{C}/h$ ).

Aljaroudi [139] used the following formula for calculating sweat rate [140], the heat storage [141]:

$$\begin{aligned} & \text{Sweat rate (SR) (L/h)} \\ & = \frac{\text{pre-exercise } W(\text{kg or L}) - \text{post-exercise } W(\text{kg or L}) + \text{fluid intake (L)} - \text{urine volume (L)}}{\text{exercise time in hours}} \end{aligned}$$

where  $W$  = body weight.

The following equation [141] was used to calculate heat storage:

$$HS(\text{watts/h}) = W(\text{kg}) * (\text{post\_exercise } T_c - \text{pre\_exercise } T_c)$$

\* specific heat capacity of body tissue(0.97watts/h/kg/°C)

where W = body weight and Tc = core body temperature.

## Subjective evaluation

According to Montemezzo [142], the clothing, acts like an extension of the body such as a ‘second skin’. Considering the direct contact between garment and users, the ergonomic information is critical for the development of PCGs that are individualized to different needs of various user groups. Ergonomic design that considered the user’s acceptance and preference is important to develop a satisfactory and comfortable product. To evaluate subjective preference, some parameters such as thermal comfort, movement comfort, fit, usability were proposed. Normally, category scales are employed when assessing the individual preference, Table 1 provides some examples for the assessment scales in occupational field.

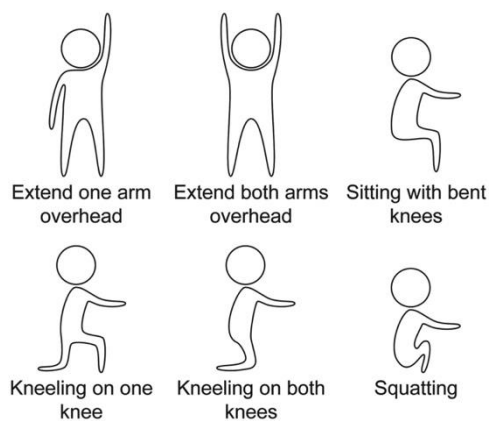
**Table 2.2** Subjective assessment scales.

Perceptual responses	Assessments
Thermal sensation	9-point thermal sensation scale [86]
	Thermal Comfort Scale [139]
	Nielsen questionnaire [106]
	7-point scale [35] [134] [143]

Thermal comfort	5-point thermal comfort scale [82] [86]
	10-point scale [33]
	Nielsen questionnaire [106]
Skin wetness sensations	5-point scale [82]
	10-point scale [33]
	7-point scale [92] [35]
	Nielsen questionnaire [106]
Skin dryness sensation	7-point visual analogue scale [143]
Clingy sensation	7-point thermal comfort scale [35]
Ratings of perceived exertion	15-point Borg scale [82]
	Borg CR-10 scale [92] [139]
	7-point scale (six different postures) [82]
	11-point scale [143]
Movement comfort evaluation	7-point scale [82]
	5-point scale [86]
	6-point Likert scale [95]
Movement restriction	5-point subjective scale [134]
Overall well-being	10-point scale [33]
Fitness	5-point scale [86]
	6-point Likert scale [95]
	7-point visual analogue scale [143]
Effectiveness	7-point visual analogue scale [143]
Preference	7-point visual analogue scale [143]

Usability	6-point Likert scale [95]
	5-point scale [86]
Aesthetic design	6-point Likert scale [95]

Except for the subjective assessment scales that are listed in Table 2.2, Zheng et al. [82] proposed a movement comfort evaluation through six different postures [144] (Fig 2.19).



**Figure 2.19** Schematic diagram of postures performed for the movement comfort evaluation.[144]

And based on the research of Al Sayed [33], Ngô et al. [145] used an ergonomic criterion to validate the Air/CO<sub>2</sub> cooling garment. Eight experts (from both the academic and mining sector) proposed a usability matrix. Participants were asked to execute typical movements that associated with mining work [146] to complete a 6-point Likert scale for five criteria and assess the Air/CO<sub>2</sub> cooling garment. After the assessment, a mind map which represent the criteria and their relationships were proposed. The results indicated that the questions were sufficiently discerning.

Meanwhile, some parameters for assessing individual responses such as the perceptual strain index (PeSI), the physiological strain index (PhSI) were calculated through equations [147-149]. The PeSI has been recommended as a reliable tool for assessing perceptual levels of heat strain in occupational settings [150, 151].

Aljaroudi et al. [139] using the following equation developed by Tikuisis et al. [147] to calculate the PeSI,

$$\text{PeSI} = \frac{5 \cdot (T_s - 0)}{8} + \frac{5 \cdot \text{RPE}}{20}$$

where  $T_s$  = thermal sensation and RPE = rating of perceived exertion.

Chan et al. [143] used the modified the PeSI which based on Tikuisis et al. [147] to indicate the perceptual heat strain,

$$\text{PeSI} = 5 \times \text{RPE}/10 + 5 \times (\text{TS} - 1)/6$$

where TS is a modified rating scale for thermal sensation from 1 to 7, and RPE adopts an 11-point scale for physical exertion from 0 to 10.

Aljaroudi et al. [139] used the following equation which was adapted from Moran et al. [152] to calculate the physiological strain index:

$$\text{PhSI} = \frac{5 \cdot (\text{post-exercise } T_c - \text{pre-exercise } T_c)}{(39.5 - \text{pre-exercise } T_c)} + \frac{5 \cdot (\text{post-exercise HR} - \text{pre-exercise HR})}{(180 - \text{pre-exercise HR})}$$

where HR = heart rate and  $T_c$  = core body temperature.

The choice of PCGs is based on subjective judgments such as sensorial comfort,

personal interests and clothing attributes. For instance, various sensations were applied when assessing the sensational property, including thermal sensation, skin wetness sensation and movement comfort evaluation. And some clothing attributes like fitness, usability and aesthetic that are also related to the performance evaluation of PCGs. However, people's preferences generally vary from person to person, it changes with the environment, age and type of work. For PCGs, the individual preference is a personal desire that people can satisfy themselves within choices available. In addition to the evaluation scales, some postures were designed for movement comfort evaluation, and equations were developed to calculate the PeSI and the PhSI. Nevertheless, there is no standard for individual preference. The detailed ergonomic criterion based on the working scenarios should be established for the evaluation of PCGs.

### **Human thermoregulation model**

The human thermoregulation system functions to maintain a constant body core temperature within a narrow range between 36-38 °C(normal range at rest) [153] by both behavioral and physiological means under different environmental conditions. The human body exposed to extreme environmental conditions or performing highly intensity exercise can result in poor regulation of body core temperature thus inducing hyperthermia and hypothermia. Thermoregulation models which can simulate physiological responses and complex heat transfer of the human body were developed to predict human thermal responses in different environmental and activity conditions [154]. It is a good alternative to human trial studies to avoid the ethical problems and

operating limitations. In recent years, various thermoregulation models have been developed.

Thermoregulation models can represent the human body as a single unit or multiple body segments. These models can be categorized into node thermal models and multi-element thermal models [155]. Node thermal models include one-node, two-node, and multi-node variations. One-node models predict thermal responses using formulas derived from experimental conditions, treating the human body as a single unit without incorporating a thermoregulatory system. Two-node models, such as Gagge's model, divide the human body into core and skin shells, each with a uniform temperature. This well-known model simulates skin and core temperatures under uniform and transient environmental conditions with moderate activity levels [156]. Multi-node human thermal models extend the two-node approach, considering an inhomogeneous distribution of temperature and thermoregulatory responses over the body's surface. Advanced vasomotion models within multi-node models can simulate local skin temperatures of individual body parts. Stolwijk developed the most influential multi-node model, which laid the foundation for many subsequent human thermal-modelling studies [157]. Although designed to investigate changes during heat stress situations and including control equations for cold exposures, the model's predictability during cold exposures was limited, and it is restricted to constant environment conditions [158].

## 2.6 Summary

PCGs have emerged as an effective solution for individuals to regulate their thermal comfort and enhance work performance. There are three primary types of commercially available PCGs: ACGs, LCGs, and PCCGs. However, each type has its own set of limitations. ACGs are lightweight but their cooling performance is limited by environmental conditions, and direct wind on the waist can cause discomfort. LCGs and PCCGs are too heavy for everyday clothing, restricting the duration of cooling. Furthermore, the temperature of the liquid or phase change material and the condensation of sweat may lead to user discomfort. Evaporative cooling garments, as active cooling garments, are unable to provide adequate cooling for most applications and are also constrained by environmental conditions. Other cooling garments, such as radiative and TE cooling garments, are still in the development phase and have not yet been commercialized.

As a relatively lightweight cooling garment, the cooling efficiency of ACGs is sensitive to environmental factors such as humidity levels and air temperature. In highly humid and extremely hot conditions, the cooling effect may be less pronounced. Active ACGs require a power source to operate, which can be problematic in situations where a continuous power source is not readily available. Passive ACGs, triggered by body movements and natural convection, show limited cooling efficiency, although they are lightweight and do not require extra devices, making them suitable for sportswear. For the design of active ACGs, the fabric of the outer layer should be considered for air

circulation inside the clothing, and incorporating features such as eyelet design and adjustable openings can prove beneficial in mitigating the bulkiness problem. Furthermore, optimizing the placement of devices with higher flow rates in the sweating region is recommended to enhance cooling efficiency.

The suitability of LCGs and PCCGs as normal clothing is limited by their excessive weight, which in turn affects the duration of cooling provided. The weight can add bulk, making them less comfortable and practical for everyday use, especially in athletic settings. LCGs and PCCGs typically have a limited cooling duration, and their cooling sources need to be recharged or replaced to maintain function. This limitation can be a concern for individuals requiring long-lasting cooling, such as athletes during extended competitions. Developing and manufacturing PCCGs with advanced cooling technologies (such as tubing system design of LCGs and PCMs with different melting temperatures) can be expensive, which can limit their accessibility to a wider range of users. Furthermore, the low temperature of the cooling liquid or phase change material and the potential condensation of sweat can lead to user discomfort. In terms of LCGs, optimizing the cooling performance involves utilizing a lower liquid temperature coupled with a higher flow rate (not exceeding 1L/min). Additionally, the design of adjustable (fitness and flows) LCGs can minimize discomfort resulting from direct contact between the coolant and the skin. For PCCGs, enhancing cooling efficiency can be achieved by increasing the mass of PCMs or PCM microcapsules. Lower melting temperatures of the PCM provide higher cooling rates. It is important to note that the

use of ice packs should only be considered when there is sufficient thermal resistance between the skin and the ice to prevent any adverse effects. Finally, achieving a proper fit of LCGs and PCCGs is essential to enhance cooling efficiency.

The performance of ECGs is influenced by ambient temperature and humidity, posing a potential limitation. ECGs can only lower body temperature to a certain extent. In extremely hot or humid conditions, they fall short of providing adequate cooling, especially for individuals engaged in strenuous activities. To enhance the cooling performance of direct ECGs, firstly, increasing the liquid content and ensuring direct contact between the fabric and the skin can enhance cooling efficiency. Secondly, reducing the evaporative resistance and thickness of the fabric used in ECGs can promote improved cooling effects. However, the detailed exploration of other cooling garments, such as TCGs and RCGs, remains relatively limited in current research. Thus, further investigations in these categories are warranted to expand our understanding and guide future advancements in this field.

The design of PCGs is a critical factor in their cooling performance, with three main considerations: function, ergonomics, and aesthetics. For ACGs, key design elements include the outer layer fabric, air distribution system, and clothing eyelets, as these components influence the circulation of cooling air inside the garment. In contrast, PCCGs and LCGs require careful consideration of the coverage area, temperature of cooling materials, and clothing fit. Evaluating PCGs is an essential step in the design

process, typically involving manikin tests, human subject tests, and model simulations, although these methods have limitations in practical applications. Notably, the cooling performance of a PCG can vary significantly under different environmental conditions, and the application scenario plays a crucial role in determining the cooling efficiency of various PCG types.

The development of effective PCGs requires a comprehensive approach that considers various factors, including cooling performance, application scenario, user experience, and human factors. This study aims to address these critical aspects by investigating the design and optimization of PCGs tailored to specific end-use scenarios. By focusing on the balance between function, ergonomics, and aesthetics, the research seeks to enhance the efficiency and usability of PCGs in different applications. Furthermore, this study explores the impact of human factors on individuals' responses while wearing cooling garments under normal working conditions. The insights gained from this research will contribute to the advancement of PCGs, ultimately leading to improved comfort and productivity for users in various settings. The findings of this study have the potential to guide future research and development efforts in the field of personal cooling garments for more effective and user-friendly solutions.

# **Chapter 3 Design of Personal Cooling Garment for Healthcare Workers in Hospital Environment**

## **3.1 Introduction**

The global COVID-19 pandemic has highlighted the critical role of healthcare workers in responding to the virus. The World Health Organization estimated that 115,493 healthcare workers have died due to COVID-19 [159]. Healthcare professionals frequently work in environments with a high risk of viral transmission. Personal Protective Equipment (PPE) as an essential component of isolation precautions, which was designed to protect these individuals from potential exposure to infectious agents [160, 161]. However, prolonged use of PPE can lead to additional physical and mental stress, such as heat strain, fatigue, and a potential decrease in work performance [162-165]. A study revealed that healthcare professionals experienced heat strain symptoms approximately 25 times more frequently when working with PPE compared to working without it [166].

To alleviate the heat stress caused by PPE, personal cooling garments were developed to enhance heat loss and improve thermal comfort by regulating body temperature and reducing physiological stress. Several studies have evaluated the effects of existing personal cooling garments used with PPE, including PCM/ice vests [167-169], liquid cooling garments [139, 170-172], and ventilation cooling systems [173, 174], all of which demonstrated significant improvements in thermal comfort. However, PCM/ice

vests and liquid cooling garments have limitations in operating time [53, 57], and both of these cooling methods can cause skin wetness, which affects skin wetness comfort [175]. Additionally, existing air cooling systems are impractical in environments with highly contagious infections, as they require air intake from the surroundings. Considering the limitations of existing cooling technologies, we developed a novel and lightweight wearable cooling and dehumidifying system (WCDS) for use in hazardous environments to reduce skin wetness and improve thermal comfort.

This chapter focuses on the design and development of a personal cooling garment specifically tailored for indoor hospital environments. The primary motivation behind this project is to create a comfortable and effective cooling solution that can be easily integrated into the daily routines of healthcare professionals. By addressing the unique challenges faced in hospital settings, this personal cooling garment aims to improve thermal comfort, reduce heat stress, and contribute to better patient care.

## **3.2 Design requirements**

### **3.2.1 Functional and performance requirements**

#### **Cooling performance**

- 1). The garment should effectively take away heat and moisture from the skin surface to maintain a comfortable microclimate [176].
- 2). The garment should be capable of maintaining the desired cooling effect throughout

its intended use duration for a minimum of 4 hours, corresponding to the average duration of a healthcare worker's shift.

### **Uniform cooling distribution**

The cooling elements should be strategically placed to target key heat-sensitive areas, such as the chest and back area [53].

### **Compatibility with personal protective equipment (PPE)**

- 1). The cooling garment should be designed to be worn comfortably under standard hospital PPE, without impeding movement or causing bulkiness [177].
- 2). The garment should not compromise the integrity of the PPE, ensuring compliance with hospital infection control protocols [178].

### **Ease of use and maintenance**

- 1). The garment should be easy to put on and take off, with minimal assistance required, to facilitate quick and efficient donning and doffing procedures.
- 2). The cooling system should be designed for easy cleaning and disinfection, following hospital hygiene standards and infection control guidelines [178].
- 3). The garment should be durable and able to withstand regular cleaning and disinfection cycles without compromising its cooling performance or structural integrity.

### **3.2.2 Ergonomic and comfort requirements**

#### **Sizing, fit and weight**

- 1). According to ISO 8559-1, the garment should be available in a range of sizes to accommodate diverse body types and ensure a proper fit for healthcare workers.
- 2). The garment should allow for easy adjustment of fit, such as through the use of elastic materials or velcro fasteners, to adapt to individual preferences.
- 3). The garment should consider the burden on the wearer and prevent fatigue during prolonged use [179].

#### **Mobility and range of motion**

- 1). The garment should allow for unrestricted movement and full range of motion, enabling healthcare workers to perform their duties without restriction [177].
- 2). The garment design should minimize bulk and stiffness, particularly in areas such as the joints, to prevent discomfort during movement.

#### **Ease of donning and doffing**

- 1). The garment should be designed for quick and easy donning and doffing to minimize the risk of contamination and facilitate rapid response in emergency situations [177].
- 2). The garment should incorporate features such as wide openings and intuitive fastening mechanisms to enable donning and doffing with minimal assistance or training.

### **3.2.3 Safety and health requirements**

#### **Mechanical safety**

- 1). The garment should be free from sharp edges or rough surfaces, that may cause injury or damage to the wearer.
- 2). The garment should maintain its structural integrity and not pose a risk of entanglement during use, storage, or maintenance.

### **3.3 Concept generation and selection**

#### **Brainstorming and idea generation**

Firstly, the brainstorming sessions were conducted with a diverse team, including experts from related fields, such as engineers, researchers and professors, to generate a broad range of ideas and concepts[180]. We then translated the most promising ideas generated during brainstorming into visual representations, such as sketches and diagrams, to better communicate and evaluate the design [181].

#### **Evaluation and selection of design**

After finishing the concept sketches, we established a set of evaluation criteria based on the design requirements, such as cooling performance, ergonomics, safety, and ease of use, to assess the advantages of each concept [182]. Then identified the top-ranking prototype and refine them further based on the feedback and insights gained during the evaluation process, addressing any weaknesses or potential improvements [183].

## **Selected prototype**

After the initially assessment process, we will select the most suitable prototype that best satisfy the design requirements and align with the project objectives, considering factors such as feasibility, cost, and potential impact [184]. A detailed prototype description will be created, including the main components, materials, and technologies to be used, as well as a high-level overview of the manufacturing and assembly processes [183]. Then testing the selected design them in simulated hospital environments [185], and seek feedback from healthcare professionals and end-users, to gather insights and suggestions for further improvements or refinements [186].

According to the design process procedure, detailed information about prototype development is provided in Section 3.4.

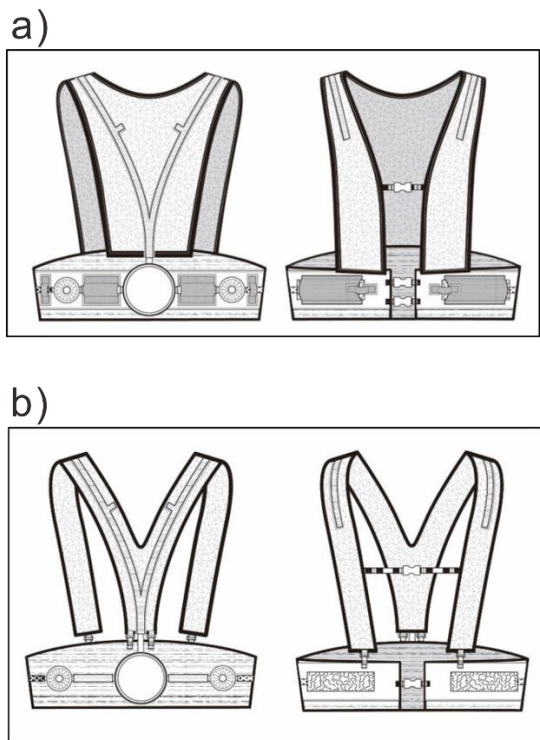
## **3.4 Design and development of prototypes**

### **3.4.1 Clothing design**

#### **Pattern**

Based on our comprehensive investigation of various designs and applications of cooling garments presented in Chapter 2, we developed two distinct prototypes. As illustrated in Fig. 3.1, Prototype 1 was inspired by Zhai's design [32], featuring a basic vest structure on the upper body to securely hold the cooling tubes, as well as a waistband designed to support and stabilize the entire cooling system. This

configuration aimed to ensure effective cooling while maintaining ease of use and structural integrity. Building upon the insights gained from Prototype 1, we designed Prototype 2 with a focus on enhancing both thermal comfort and wearability. Specifically, Prototype 2 reduces the coverage area of the upper section compared to Prototype 1, thereby minimizing potential heat retention and improving the overall comfort for the wearer during extended use. Through these iterative design modifications, we aimed to balance cooling efficiency with user comfort and practicality.



**Figure 3. 1** Schematic design of the basic vest. a) Prototype 1. b). Prototype 2.

## **Material**

After completing the pattern design, we proceeded to select suitable materials to ensure the garment's intended functionality. Our initial choice was a 3D spacer fabric (Fig.

3.2a and b), as its structure naturally provides space for embedding tubes and offers sufficient support for the cooling system. However, during the cutting and sewing process, we encountered several challenges. First, it was difficult to cut precise holes for the tubes, which affected the overall fit and finish. Second, the mesh fragments produced during cutting could potentially cause discomfort to the wearer. Third, the thickness of the fabric made it challenging to sew, complicating the assembly process. These issues led us to reconsider the use of 3D spacer fabric and explore alternative materials that could better meet the requirements of our cooling garment design.

a)



b)



**Figure 3. 2** Two prototypes with same material.

After encountering challenges with traditional cut-and-sew methods, we explored alternative technologies. We identified advanced digital knitting technology as a promising solution for constructing the prototype. By utilizing digital knitting, we

eliminated the need for cutting and sewing, as the garment could be produced seamlessly in a single process. This approach also allowed us to incorporate specialized channel designs for the cooling tubes, as well as additional structural components, directly into the fabric during production.

The seamless construction was achieved using high-quality polyester filament yarn, which not only enhances the garment's durability but also improves wearer comfort. To further increase comfort and provide additional support for the cooling system, a foam pad was integrated into the waistband section. As illustrated in Figure 3.3, this method facilitates easy integration of all necessary components.

The prototype features both a waistband and a back strap. The waistband is designed with an embedded L-shaped channel to securely house electronic devices, and a double-sided channel wall, created by floating yarns, ensures a seamless and robust structure. The back strap incorporates a Y-shaped double-channel configuration, which enhances fit and comfort for the wearer.

To accommodate a wide range of body types and sizes, the garment includes adjustable features such as hook-and-loop fasteners and buckle fasteners at the chest and waist, allowing for a secure and customizable fit. The tubing system's branching structure has been carefully optimized: the diameters of the secondary branches and the primary channel are set at 9 mm and 12 mm, respectively, resulting in a diameter ratio of 0.75.

This ratio is designed to minimize flow resistance, thereby improving the efficiency of the air ventilation system [20]. The foam structure in the waistband not only supports the weight of the entire system but also enhances overall comfort during wear. Importantly, the entire system is designed to be detachable, making it easy to remove and wash the garment as needed.



**Figure 3. 3** Front and back view of the knitting undervest.

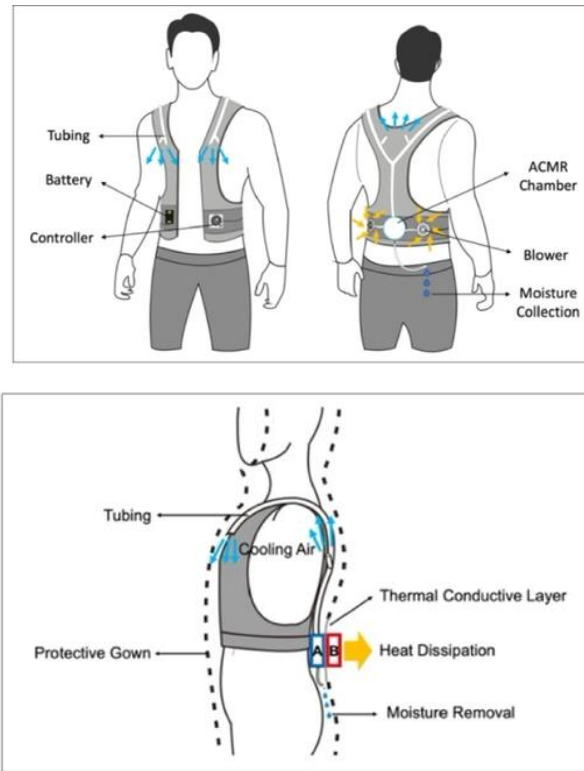
### **3.4.2 Cooling system design**

The cooling system is a critical component of the wearable cooling and dehumidifying system (WCDS), designed to provide efficient cooling and moisture removal for enhanced thermal comfort. The system which developed by Lou.et al[81] consists of two main parts: part A, which enables internal air circulation within the protective clothing, and part B, a thermoelectric (TE) cooling unit located outside the protective garment (Fig. 3.1a).

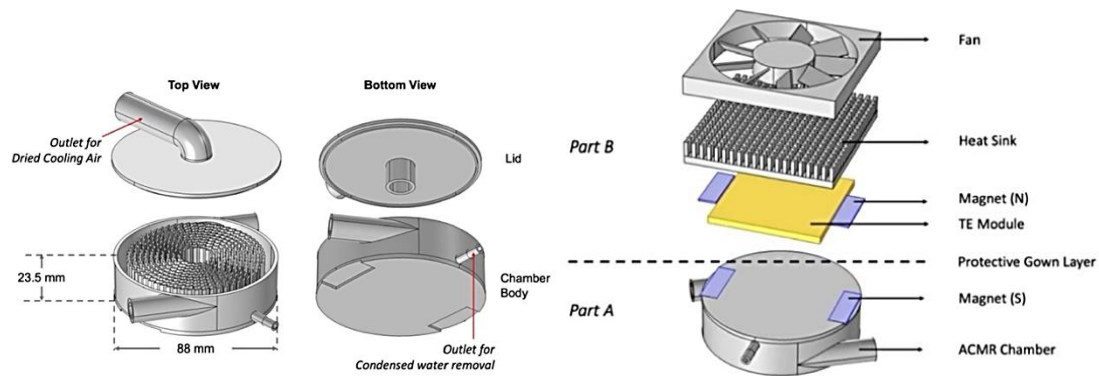
In part A, air is pumped into the air cooling and moisture-removal (ACMR) chamber

by two blowers from the left and right sides. The cooled air is then distributed to the upper chest and upper back areas through a tree-like branching tubing system, which includes a primary channel and secondary branches (Fig. 3.1b). The waist-mounted cooling delivery system provides cooling through cold air cooled by the TE unit. The ACMR chamber body is designed to encourage dropwise condensation of moisture for easy removal, while the plastic lid features an L-shaped air outlet that connects to the tree-like tubing system for efficient cooling air distribution.

Part B of the cooling system includes a TE module integrated with a heat dissipation system, consisting of a pin-fin aluminum heat sink and an axial fan. The axial fan directs ambient air towards the pin-fin heat sink to enable effective heat dissipation. Part A and part B are powered separately by two batteries to ensure optimal performance and convenience. The part A battery is located inside the protective garment, while the part B battery is attached to the exterior using magnetic bonding, allowing for easy replacement without removing the protective clothing.



(a)



(b)

**Figure 3. 4** a) Schematic diagram of the wearable cooling and dehumidifying system (Front, back and side view). b) ACMR chamber body and schematic diagram of cooling system (part A and part B). [81]

## Material selection

The cooling system components were selected based on their specific properties and performance requirements. The chamber body of the ACMR is fabricated through selective laser melting (SLM) 3D printing with aluminum alloy AlSi10Mg, followed

by a 300 °C heat treatment. The inner surface of the chamber body is spray-coated with a superhydrophobic layer (Rust-Oleum, NeverWet) to encourage dropwise condensation. The lid of the ACMR is fabricated through stereolithography (SLA) 3D printing with resin UTR 9000E.

The micro-blowers (Model DSB5525V24HB-TK) and the fan (Model D8015V12SLB-TK, 80\*80\*15 mm) are purchased from Activa Inc. The thermoelectric module (Model TEC1-12730, 62624 mm) is sourced from Sirui Electronics Inc, while the pin-fin aluminum heat sink (Model 2080-12W, 80\*80\*12 mm) is obtained from Alpha Novatech Inc. Latex tubing (Shanghai Hongying Technology Inc.) with inner diameters of 12 mm for the trunk & main branches and 9 mm for the secondary branches is used for the air distribution system. The batteries (11.1V, 3000mAh) are custom-made by connecting three lithium batteries (Yuhuida Electronics Ltd., Model 505080: 3.7V 3000mAh) in series.

### **3.4.3 Integration of cooling components into the garment**

The assembly process of the WCDS involves the integration of the cooling system components into the undervest garment. The ACMR chamber is securely positioned within the waistband section, with the tubing system routed through the designated channels in the undervest. The blowers are connected to the ACMR chamber, and the thermoelectric cooling unit is attached to the exterior of the protective garment through magnetic bonding.

All electrical connections are double-checked to ensure proper functionality and safety.

The undervest is then subjected to a final quality control inspection to verify the proper integration of all components and to ensure a comfortable and secure fit.

### **3.5 Design Evaluation and Testing**

To comprehensively assess the performance and effectiveness of the wearable cooling and dehumidifying system (WCDS), a series of evaluation and testing procedures will be performed. These tests will provide valuable insights into the system's cooling capacity, thermal comfort enhancement, and overall functionality in simulated hospital environments. The evaluation and testing process will consist of two main components: thermal manikin testing and human subject testing.

#### **3.5.1 Thermal manikin test**

Thermal manikin testing is a well-established method for evaluating the cooling performance of personal protective equipment and clothing systems. In the context of the WCDS, thermal manikin testing will be conducted to quantitatively assess the system's ability to remove heat from the simulated human body and maintain a comfortable thermal environment.

The thermal manikin tests will be performed in a controlled environmental chamber, where temperature and humidity levels can be precisely regulated to simulate hospital

settings. The manikin, equipped with sensors and heating elements, will be dressed in the WCDS and other compared cooling garments, and the thermal insulation, evaporative resistance and heating power will be recorded during testing period. The thermal manikin testing methodology, test protocols, and data analysis techniques will be described in Chapter 4 of this thesis. The results obtained from these tests will provide a comprehensive understanding of the WCDS's cooling performance and any necessary design optimizations.

### **3.5.2 Human subject testing**

While thermal manikin testing offers valuable quantitative data on the WCDS's cooling performance, it is essential to evaluate the system's effectiveness and user acceptance in real-world scenarios. Human subject testing will be conducted to assess the thermal comfort, ergonomics, and overall user experience of participants wearing the WCDS during daily activities.

A carefully designed human subject study will be carried out. Participants will be asked to wear the WCDS during working period and provide feedback on their thermal comfort, ease of movement, and any perceived benefits or limitations of the system.

The key aspects of human subject testing will include:

- 1) Physiological measurements, such as skin temperature and heart rate, to evaluate the body's thermoregulatory responses

2) Subjective thermal comfort assessments using standardized scales and questionnaires. Ergonomic assessments to ensure that the WCDS does not hinder the wearer's movements or interfere with their work tasks.

The detailed methodology, participant recruitment process, data collection, and analysis procedures for the human subject testing will be presented in Chapter 5 of this thesis. The insights gained from this study will be invaluable in validating the WCDS's effectiveness in enhancing thermal comfort and user experience in simulated hospital environments.

# **CHAPTER 4 Comparative Study of Personal Cooling Garments for Healthcare Workers Based on Thermal Manikin Tests**

## **4.1 Introduction**

This chapter presents a systematic evaluation of the cooling performance of our newly developed Wearable Cooling and Dehumidifying System (WCDS) designed specifically for healthcare workers. Building upon the design parameters and initial concept generation detailed in Chapter 3, we now transition from theoretical design to cooling performance assessment through thermal manikin.

While the lightweight cooling garment (WCDS) was developed with careful consideration of healthcare workers' unique needs and constraints, its thermal management effectiveness must be objectively quantified before clinical application. This chapter addresses this critical need by employing the perspiring thermal manikin "Walter", which offers two significant advantages: 1) it enables precise, reproducible measurements of heat and moisture transfer properties that would be difficult to standardize with human subjects; 2) it facilitates direct performance comparisons between our WCDS prototype and commercially available cooling garment currently on the market. This comparative analysis is particularly important for establishing the relative advantages of our design innovations in the context of existing technologies. By testing these cooling garments on the perspiring manikin, we can quantify cooling

capacity, duration and efficiency under conditions that closely approximate real-world usage scenarios.

## **4.2 Methods**

### **4.2.1 Clothing ensembles**

#### **Personal cooling garments**

A new designed cooling garment [81] and three different types commercial cooling garments were tested in this study (Figure 4.1), and their cooling methods and weight are listed in Table 4.1.

#### **Wearable cooling and dehumidifying system (WCDS)**

The newly designed WCDS consisted of a basic undervest and a cooling system which includes an ACMR chamber, with two blowers and the battery.

#### **Three commercialized cooling garments**

##### **Air cooling garment**

ACG by BSHORSE. This cooling garment consisted of a nylon outer shell and a mesh inner shell, with a zipper and two ventilation fans, these two fans were powered by power bank through a USB port. It worked by blowing air onto the body and increasing

evaporation of sweat on the skin surface and improving the convective cooling by increasing the air movement at the skin surface.

### **Phase change cooling garment**

PCCG by Sunny Smile. This PCCG consisted of an insulated nylon vest with 4 pockets (2 in front and 2 in back) which hold phase change material (PCM) packs. The freezing point of PCM was nearly 0°C, these packs were frozen in a freezer before testing. Body heat carried to skin surface was absorbed by the PCM in the melting process.

### **Liquid cooling garment**

LCG by COMPCOOLER. This LCG was a nylon shell vest with micro tubing channel routed throughout garment and a backpack for storing an ice water cooling bladder (i.e., containing a mixture of 2.0 kg ice and 1.0 kg water), a pump and battery. The pump was used to deliver cooled water from the bladder through tubing within the garment to the skin surface for exchanging the conductive heat with the body.



**Figure 4. 1** A new designed cooling garment and three commercial cooling garments.  
 1) WCDS, 2) ACG, 3) PCCG, 4) LCG.

### Personal protective equipment and basic undergarments

A standard PPE ensemble recommended for use in Hong Kong during COVID-19 consisted of a surgical mask (N95,3M), eye protection (Fahrenheit™ Safety Goggles,3M), protective gown (Tyvek 600 plus coverall, Dupont) and gloves. Basic undergarments: A cotton t-shirt and trousers from Uniqlo.



**Figure 4. 2** Personal protective equipment and basic undergarments.

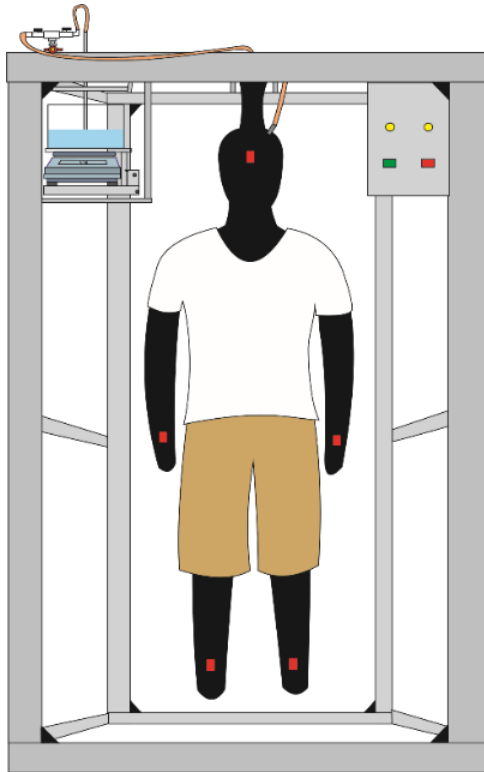
### 4.2.2 Test protocol

Manikins are the most useful tools for evaluating thermal comfort of whole clothing system. A perspiring thermal manikin--Walter, developed by Fan et al. [137] was used in this study. The manikin Walter can measure the thermal insulation and evaporative resistance which are the two most important parameters of clothing system. The manikin can also provide a reproducible evaluation of cooling power. According to the ASTM F2371, cooling power is calculated as a difference between the power input to the manikin using the cooling garment and the baseline value under the control condition.

The study was performed in a climatic chamber, which was set to 23°C, 50% relative humidity, and 0.1m/s air velocity to simulate the clean workroom in Hong Kong hospital. The perspiring thermal manikin, Walter, was set to a constant core temperature mode, and the core temperature was controlled at 37°C that corresponded to the human mean core temperature at the thermal neutral condition.

There were two test conditions (4 experimental trials) to evaluate these cooling garments. One was that the thermal manikin was dressed in PPE ensemble and basic undergarments without cooling garment (control), another condition was that the thermal manikin was dressed in the same PPE ensemble, basic undergarments and the cooling garment under test (i.e. ACG, PCCG, LCG, WCDS), respectively, with the cooling units turned on (cooling). The standard PPE ensemble recommended in Hong

Kong during COVID-19 was used for each test. All the cooling garments were worn underneath the protective clothing.



**Figure 4. 3** Perspiring thermal manikin-Walter

## **4.3 Results and discussion**

### **4.3.1 Thermal manikin test for newly designed WCDS**

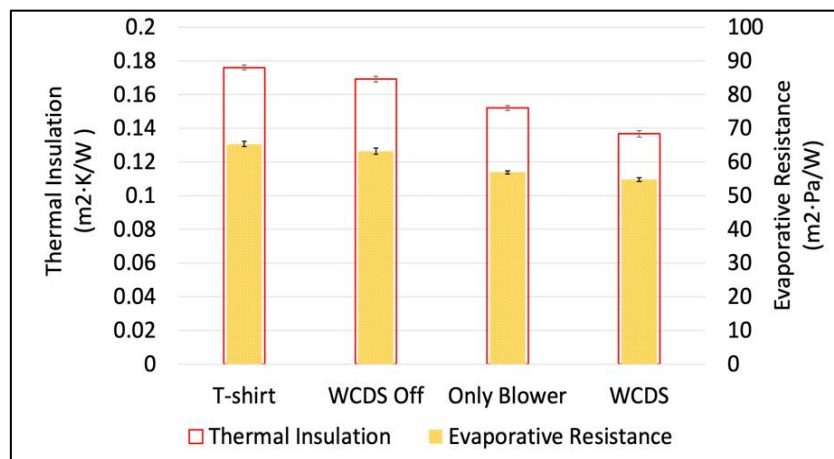
The cooling and dehumidifying efficiency of the WCDS was evaluated using a thermal manikin at 23°C/50%RH, as shown in Fig 4.4. The WCDS-Off condition, where the cooling function was turned off, exhibited lower thermal insulation ( $R_{ct}$ ) and evaporative resistance ( $R_{et}$ ) compared to the T-shirt control group due to the smaller body surface coverage of the WCDS vest.

Activating only the blowers (Only Blower) with a 5.0 W power input and a 70 L/min air flow rate significantly decreased the effective evaporative resistance, generating 32.1 W of cooling power. This resulted in a 13.6% reduction in  $R_{ct}$  and a 12.9% reduction in  $R_{et}$ , with the air temperature at the ACMR outlet measuring 31.7 °C, equivalent to the microclimate temperature inside the protective coverall.

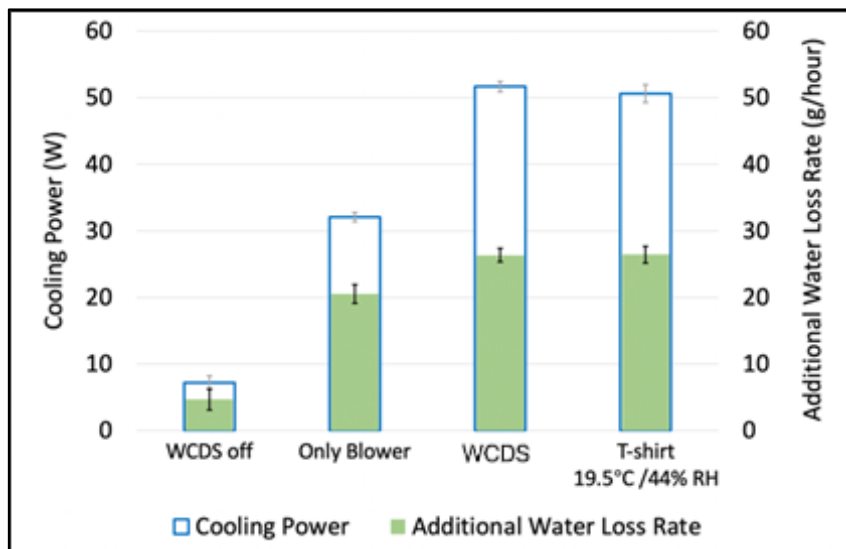
When both the blowers and TE unit were activated (WCDS group) with a total power input of 26.2 W and a 70 L/min flow rate, the system produced 51.7 W of cooling power and an additional 26.3 g/hour water loss from the manikin. This corresponded to a 22.3% reduction in  $R_{ct}$  and a 16.1% reduction in  $R_{et}$ . The ACMR outlet air temperature decreased to 25.8 °C due to the TE cooling unit and liquid alcohol at the interface, compared to 27.2 °C without the liquid alcohol. The WCDS condition increased the water loss rate by 5.8 g/hour compared to the Only Blower condition, with 4.1 g of condensed moisture collected hourly in the water container inside the protective coverall and a small amount condensing on the ACMR's outer surface. Moisture condensation and removal accounted for 7.6% of the total cooling power.

The thermal manikin test revealed that dehumidification was primarily achieved through air ventilation by the blowers inside the protective clothing, reducing the evaporative resistance by 12.9% and increasing water loss by 20.5 g/hour compared to the T-shirt control group. The TE cooling unit caused an additional 5.8 g/hour water

loss compared to the Only Blower condition due to moisture condensation inside the ACMR. The protective coverall's permeability to air and water vapor influenced the dehumidification mechanisms, with less permeable clothing relying more on moisture condensation for dehumidification.



(a)



(b)

**Figure 4. 4** Cooling and dehumidifying performance of the WCDS. (a) Comparison of clothing thermal insulation and evaporative resistance. (b) Comparison of cooling power and additional water loss rate.

### 4.3.2 Comparison of different cooling garments

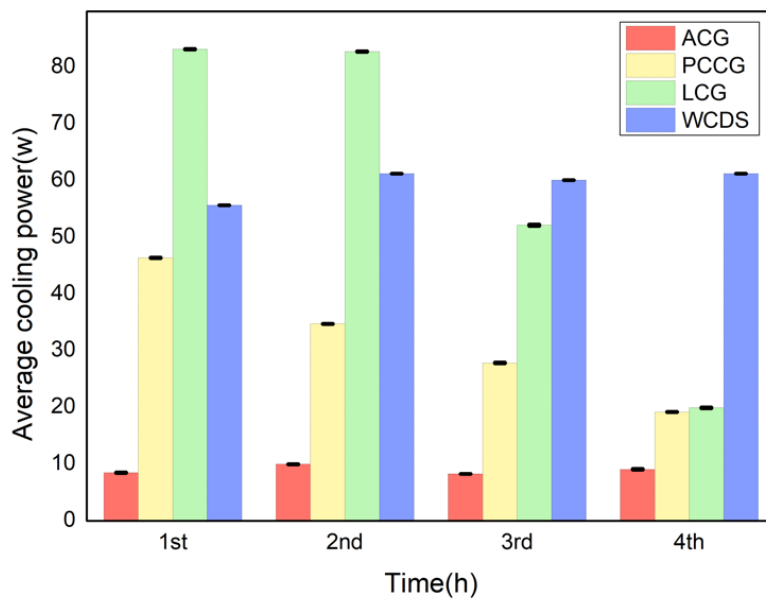
Table 4.1 compares the WCDS with three commonly used commercial cooling garments in terms of cooling method, cooling temperature (the temperature measured between the skin and cooling garment), and garment weight. The WCDS employs a combination of thermoelectric cooling and blowers, achieving a cooling temperature range of 26.5°C to 28.8°C with a total weight of 1.2 kg, including the battery. In contrast, the ACG uses ventilating fans, resulted in a higher cooling temperature of 32.5°C but is the lightest at 0.7 kg. The PCCG utilizes ice packs, enabling a significantly lower cooling temperature of 4.2°C (measured at the beginning of the cooling start), with a total weight of 1.9 kg, including the battery. The LCG combines ice water and a water circulation tubing system, maintaining a cooling temperature of 11.1°C (measured at the beginning of the cooling start), and has the highest total weight of 4.3 kg among the four garment types.

**Table 4.1** Comparison of different types of cooling garment

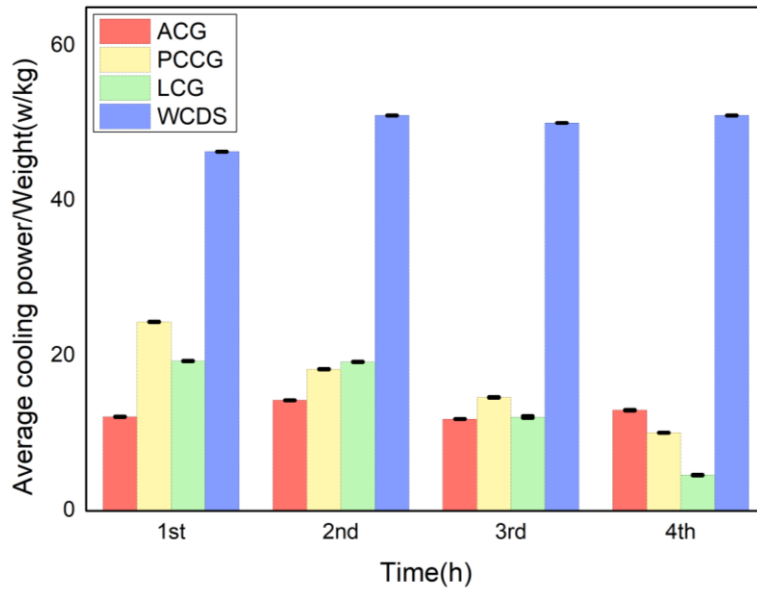
Cooling Garment Types	Cooling Method	Cooling Temperature	Total Weight (Including Battery)
WCDS	Thermoelectric & Blowers	26.5 ~ 28.8 °C	1.2 kg
ACG	Ventilating fans	32.5 °C	0.7 kg
PCCG	Ice packs	4.2 °C	1.9 kg
LCG	Ice water & Water circulation tubing system	11.1 °C	4.3 kg

The manikin test results are plotted in Figure 4.5(a-c). Since the cooling power of PCCG and LCG changed greatly over time as the ice turned into water and the temperature of water increases. Figure 4.5.a therefore presents the average cooling power of these four cooling garments (i.e., ACG, PCCG, LCG, WCDS) for the first 4 hours over one hour interval (viz. 1st hour, 2nd hour, 3rd hour and 4th hour). In the first two hours, LCG had the highest cooling power with the average value over 80 Watts, followed by WCDS, PCCG and ACG [See Fig. 4.5(a)]. However, because LCG is very heavy, in terms of the cooling power per unit weight [See Fig. 4.5 (b)], WCDS is the best and there is no significant difference between LCG, PCCG and ACG. After the initial two hours, the cooling performance of LCG and PCG dropped dramatically and lowered to about 20 Watts in the 4th hour. Comparatively, the cooling power of ACG was the lowest at about 10 Watts, but it was stable over time. Since ACG was very light, its cooling power per unit weight was similar to those of LCG and PCCG after two hours usage. In general, the overall cooling performance of the newly developed WCDS was best, as its cooling power was very stable over time at about 60 Watts and its average cooling power per unit weight was 2.9~3.9 times of the rest cooling garments over the 4 hours of testing period. As the ACG provided lower than 10 W for the whole cooling period, it could not provide sufficient cooling and did not have efficient cooling duration. At the same time, the ACG need the air intake from the surroundings, which are impractical in highly contagious infections environments. The evaporative heat transfer, which is the most effective cooling method of air cooling system, was significantly limited by the impermeable design of PPC. This resulted in its cooling

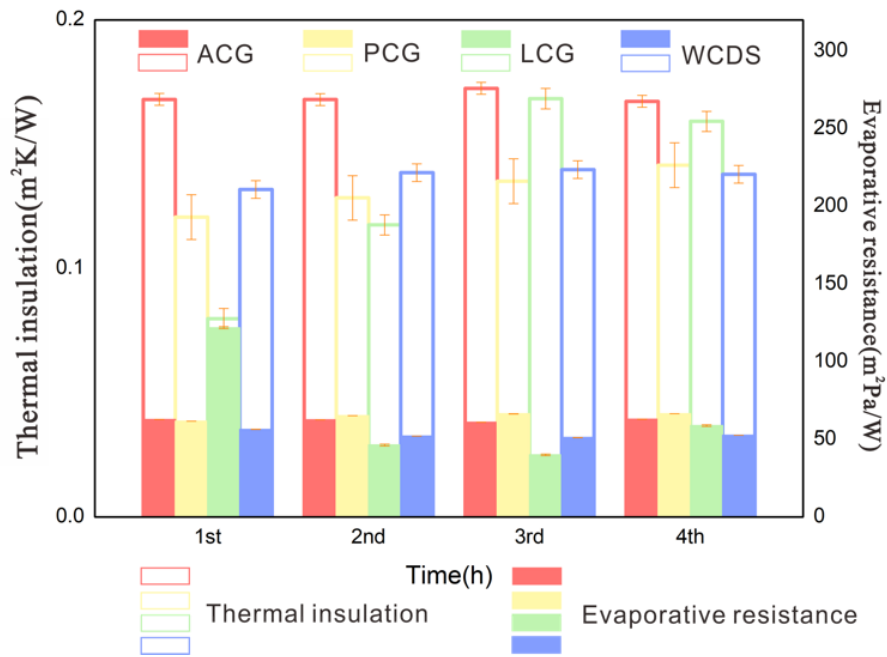
capacity barely notable. For the first 2 hours, the cooling power of LCG could meet the standard value (50w) of PCG defined by ASTM International standard F2371, but the weight of LCG may increase human metabolism. Figure 4.5 (c) compares the thermal insulation and evaporative resistance of four PCGs over a 4-hour period. The WCDS consistently maintains the lowest thermal insulation and evaporative resistance, suggesting it provides the most effective cooling. The phase change garment (PCG) and liquid cooling garment (LCG) exhibit similar moderate thermal insulation and evaporative resistance values. The ACG has the highest thermal insulation and evaporative resistance, indicating the least effective cooling among the compared garments.



(a)



(b)



(c)

**Figure 4. 5** Performance comparison of cooling garments (including ACG, PCCG, LCG, WCDS) under medical protective clothing: (a) Average cooling power within one-hour interval, (b) average cooling power per unit weight within one-hour interval, (c) Mean thermal insulation and evaporative resistance within one-hour interval.

## **4.4 Conclusion**

In this study, a novel wearable cooling and dehumidifying system was evaluated for its cooling and dehumidifying performance in comparison with three commercially available personal cooling garments through thermal manikin.

Thermal manikin tests conducted in simulated hospital conditions demonstrated the superior cooling and dehumidifying efficiency of the WCDS compared to the control group and the other cooling garments tested. The WCDS produced a stable cooling power of approximately 60 Watts over a 4-hour testing period, with an average cooling power per unit weight 2.9 to 3.9 times higher than the other cooling garments.

Among the commercial cooling garments tested, the LCG and PCCG provided higher cooling power in the first two hours, but their performance decreased significantly over time. The ACG had the lowest cooling power, which was limited by the impermeable design of the PPC.

In conclusion, the newly developed WCDS demonstrates superior cooling and dehumidifying performance, as well as stability over time, compared to the commercially available cooling garments tested. The WCDS has the potential to significantly improve thermal comfort for healthcare personnel wearing PPC in hospital settings. Further research and development of the WCDS could lead to its widespread adoption in various industries where personal protective equipment is required.

# **Chapter 5 Assessment of Wearable Cooling and Dehumidifying System Used Under Personal Protective Clothing Through Human Subject Testing**

## **5.1 Introduction**

This chapter investigates the physiological and psychological impacts of our newly developed personal cooling garment (WCDS) on healthcare workers when integrated with personal protective equipment (PPE). While Chapters 3 and 4 established the design foundations and thermal performance characteristics through manikin testing, this research addresses the gap between laboratory evaluation and real-world application during healthcare crisis scenarios such as pneumonia outbreaks.

The thermal challenges faced by healthcare professionals wearing full PPE ensembles during infectious disease outbreaks represent a unique and demanding use case that laboratory testing alone cannot fully simulate. Although our thermal manikin studies demonstrated promising cooling capacity for the WCDS, these controlled evaluations cannot capture the complex reaction between human thermoregulatory responses, psychological perceptions, and practical usability constraints in clinical settings.

To address these limitations, this chapter presents a comprehensive human subject evaluation with healthcare workers wearing the WCDS beneath standard PPE ensembles. Our assessment combines objective physiological measurements (skin

temperature, core temperature, and heart rate) with subjective evaluations of thermal perception, wearing comfort, and movement restriction, which enables us to quantify both the cooling garment's physiological effectiveness in mitigating heat strain and its impact on wearer comfort, mobility, and overall acceptance.

## **5.2 Methods**

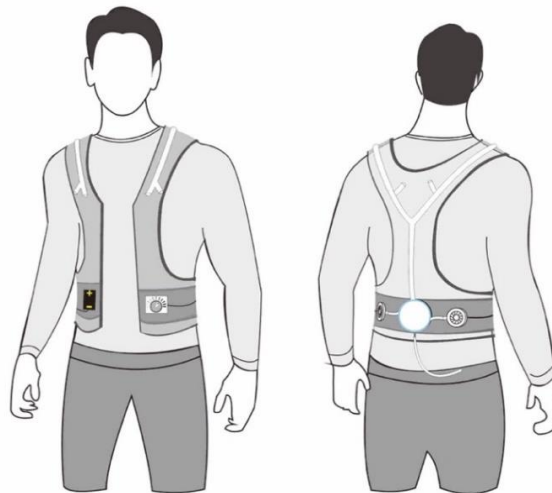
### **5.2.1 Participants**

Eight healthy male college students voluntarily participated in the study. The participants had a mean age of  $27 \pm 2.1$  years, height of  $178.3 \pm 2.2$  cm, weight of  $69.6 \pm 3.6$  kg, BMI of  $21.8 \pm 1.3$  kg/m<sup>2</sup>, and body surface area of  $1.8 \pm 0.1$  m<sup>2</sup>. Before participation, each participant was comprehensively informed about the experimental procedure and potential risks and provided with written informed consent. None of the participants had a history of heat-related illness, cardiovascular, metabolic, or respiratory disease. Additionally, they were instructed to refrain from consuming tea, coffee, or alcohol for at least 24 hours prior to each test. The Human Subjects Ethics Sub-Committee of the Hong Kong Polytechnic University approved the experimental procedures under protocol number [HSEARS20210514003].

### **5.2.2 Clothing**

The Wearable Cooling and Dehumidifying System, which developed by Lou et.al [81], is for use in hazardous and infectious environments without compromising the protective capabilities of Personal Protective Equipment (PPE). The system is designed

as a knitted vest with an embedded tube that provides cooling air. During each test, participants wore a standard PPE ensemble recommended for use during the COVID-19 pandemic, which included a surgical mask, eye protection, a Dupont Tyvek 600 plus coverall as a protective gown, and gloves. In addition to the PPE, subjects wore basic undergarments consisting of a t-shirt, trousers, underwear, and socks [187]. The WCDS was worn underneath the protective clothing. Prior to the human trials, all garments, including the cooling ones, were conditioned in a climatic chamber for 24 hours.



**Figure 5. 1** Wearable Cooling and Dehumidifying System (WCDS) [81].

### **5.2.3. Protocol**

The study took place in a climatic chamber set to 23°C, 50% relative humidity, and an air velocity of 0.1 m/s, simulating the conditions of a clean workroom in a Hong Kong hospital. Participants underwent two 120-minute experimental trials: one with a cooling clothing assembly (cooling) and the other with a control clothing assembly (without cooling). Initially, subjects were given a 30-minute acclimatization period in the chamber, during which they were briefed on the test procedures and the interpretation

of perceptual rating scales. Following this, they were instructed to change into the provided attire and were equipped with monitoring instruments. For 60 minutes, the participants walked on a treadmill at a speed of 3.0 km/hour, representing a typical work intensity level [188]. After a 30-minute recovery period, they removed their clothing and equipment and exited the chamber. To ensure safety, the test was immediately terminated if any of the following conditions were met: 1) the subject's core temperature exceeded 38°C, 2) the heart rate surpassed 95% of the average maximum heart rate, or 3) the subject expressed a desire to stop due to volitional fatigue. In such cases, subjects were scheduled to retake the same test during their next visit. It is important to note that participants had the option to stop the test at any time for any reason.

#### **5.2.4. Measurements**

##### **5.2.4.1 Physiological measurement**

Core body temperature measurements were recorded at one-minute intervals using a wearable sensor device (CORE, greenTEG). Microclimatic temperature was monitored every minute using digital thermometers (DS1923, iButton) attached inside the personal protective garment on the upper back area. Skin temperature sensors (DS1923, iButton) were placed at eight locations (forehead, left upper chest, right scapula, left and right arm, left hand and calf, and right anterior thigh) using waterproof adhesive tape (PVC, 3M). These sensors consistently recorded local skin temperatures every minute throughout the entire test period. To calculate the mean skin temperature, an eight-point weighting scheme, as specified in the ISO 9886 standard, was employed

(Table 5.1).

**Table 5. 1** Measuring sites and weighting coefficients.

Measuring sites	Forehead	Right scapula	Left Upper chest	Right arm	Left arm	Left hand	Right anterior	Left calf
Weighting coefficients	0.07	0.175	0.175	0.07	0.07	0.05	0.19	0.2

The mean skin temperature, is obtained from the following formula:

$$t_{sk} = \sum k_i t_{ski}$$

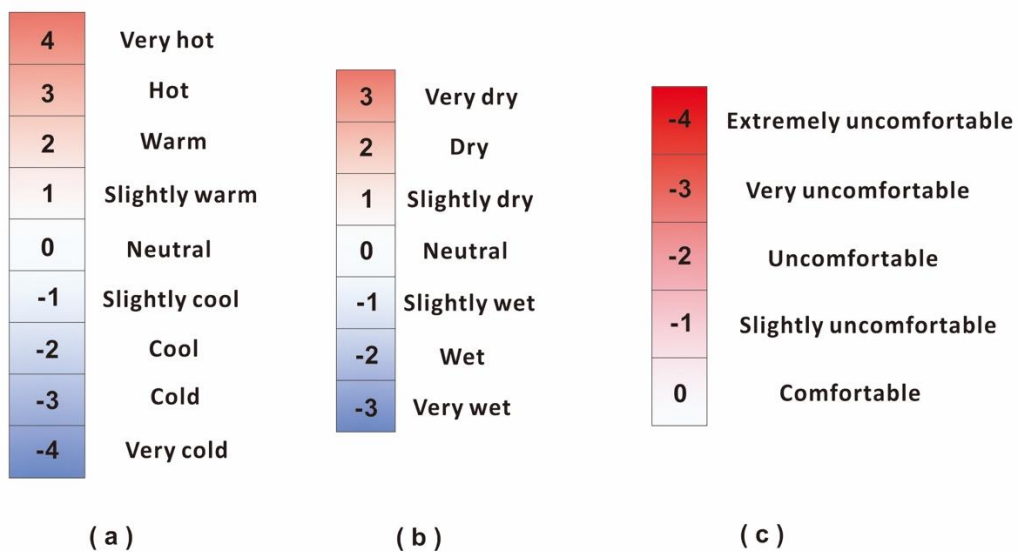


**Figure 5. 2** A subject wearing the WCDS walking on a treadmill.

#### 5.2.4.2 Subjective evaluation

Thermal sensation, wetness sensation, and thermal comfort sensation were assessed initially and then every 10 minutes throughout the entirety of the trials. The mean value was calculated for each parameter. Thermal sensation for both the whole body and the upper body was rated using a nine-point scale (Fig. 5.3a), ranging from -4 (very cold) to +4 (very hot), with 0 indicating a neutral thermal sensation. Wetness sensation for

the whole body and the upper body was measured using a seven-point scale (Fig. 5.3b), where -3 corresponds to a very wet sensation, +3 to a very dry sensation, and 0 represents a neutral wetness sensation. Thermal comfort for the whole body and the upper body was assessed using a five-point scale (Fig. 5.3c), ranging from -4 (extremely uncomfortable) to 0 (comfortable).

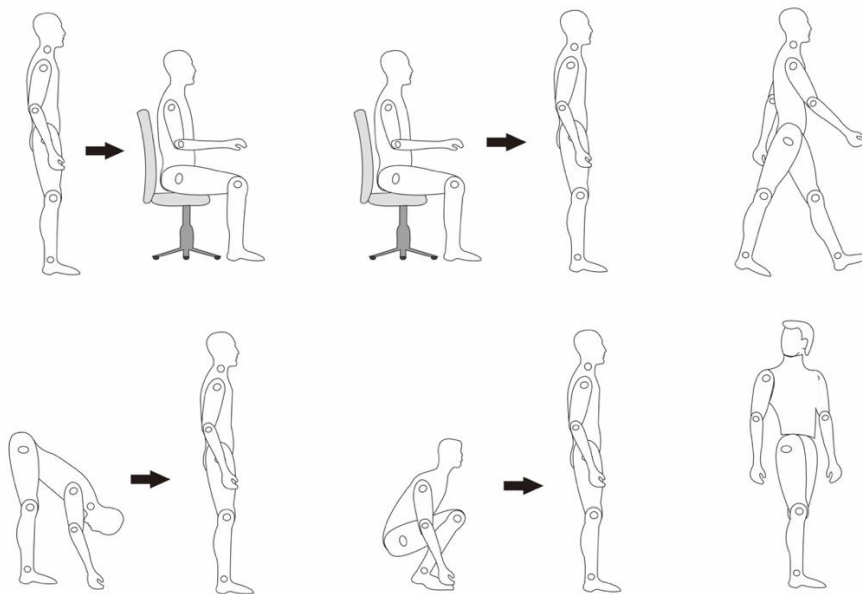


**Figure 5. 3** Subjective measurement scales (a) Thermal sensation (b) Wetness sensation (c) Thermal comfort.

### 5.2.4.3 Wearing trial

Post-experimental assessments of wearing comfort were conducted using a seven-point Likert scale, ranging from -3 (very unsatisfied) to 3 (very satisfied). The assessed criteria included ease of wearing, ease of removal, fit, flexibility, and safety. Additionally, evaluations of body movement comfort were carried out in the same climatic chamber. Participants, dressed in identical clothing, simulated six distinct postures: transitioning from standing to sitting, sitting to standing, walking, bending

forward and then straightening up, squatting and then standing upright, and twisting (refer to Fig. 5.4). After each posture, participants provided subjective ratings of their comfort and freedom of movement using a seven-point scale, ranging from -3 (very uncomfortable) to 3 (very comfortable).



**Figure 5. 4** Six different postures for body movement comfort evaluation.

### **5.2.5. Statistical analysis**

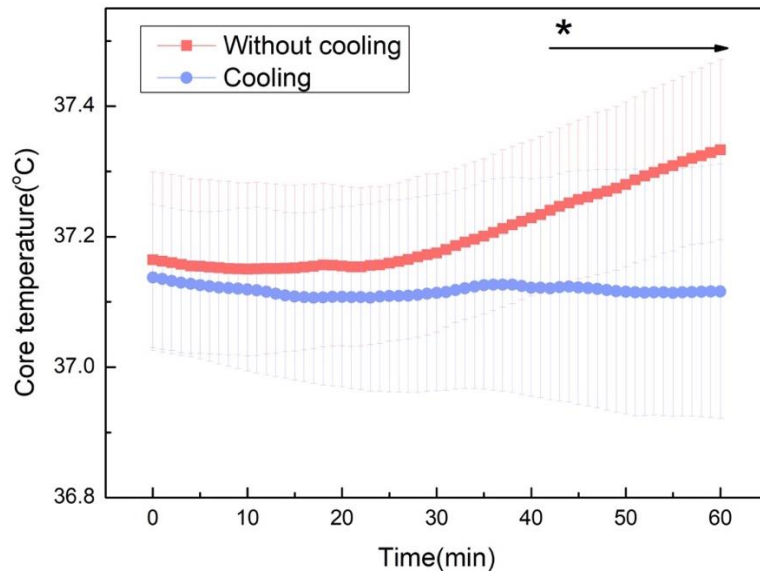
Statistical data analysis was performed using IBM SPSS Statistics (Version 19.0, IBM Corporation). Unless otherwise specified, all values are presented as mean  $\pm$  standard deviation. Paired t-tests were employed to assess both physiological and perceptual results over time and between treatments (with and without cooling). A 95% confidence level was set for all statistical analyses.

## **5.3. Results**

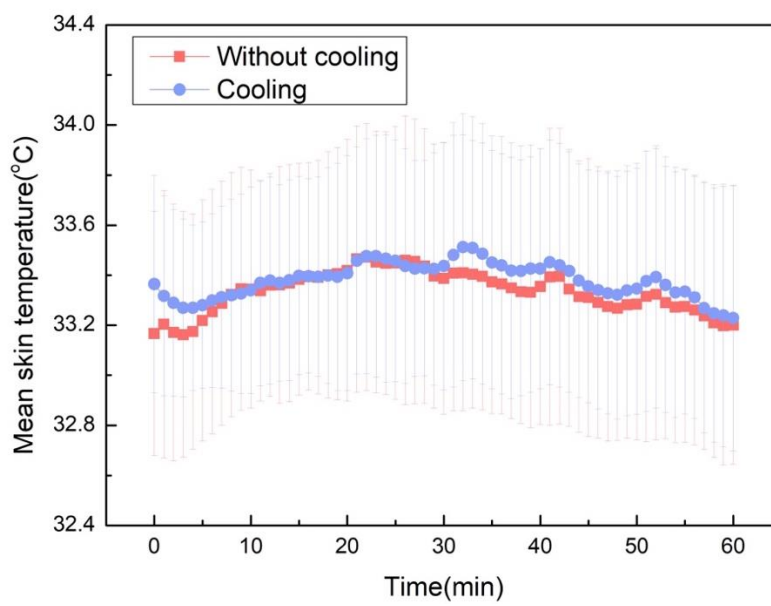
### **5.3.1 Physiological parameters**

Core temperature, mean skin temperature, and heart rate measurements were recorded at one-minute intervals. A significant difference ( $p < 0.05$ ) in core temperature between the control and cooling conditions (Fig 5.5a) was observed from the 42nd minute onwards, with a maximum difference of  $0.22^{\circ}\text{C}$  between the two conditions. Although both groups experienced an increase in core temperature throughout the exercise duration, the increase was less pronounced in the cooling group. The cooling intervention effectively maintained the core temperature at lower level compared to the non-cooling condition, demonstrating the potential benefits of cooling in maintaining a stable core temperature and preventing excessive heat accumulation. Statistical analysis revealed no significant difference ( $p > 0.05$ ) in average skin temperature between the control and cooling conditions (Fig 5.5b). The cooling group's mean skin temperature was slightly higher than that of the control group from the 29th minute of the testing period. This result could be attributed to the lower core temperature of human subject. It is known that perspiration rate is closely related to the change of core temperature. The cooling effect of the WCDS resulted in less perspiration and lower skin wetness therefore reduced the evaporative heat loss rate from the skin. The thermal conditions of the experiment were carefully selected to avoid exposing participants to severe thermal stress, simulating real hospital and working conditions while ensuring participant safety under protective clothing. Regardless of the test variant, with or

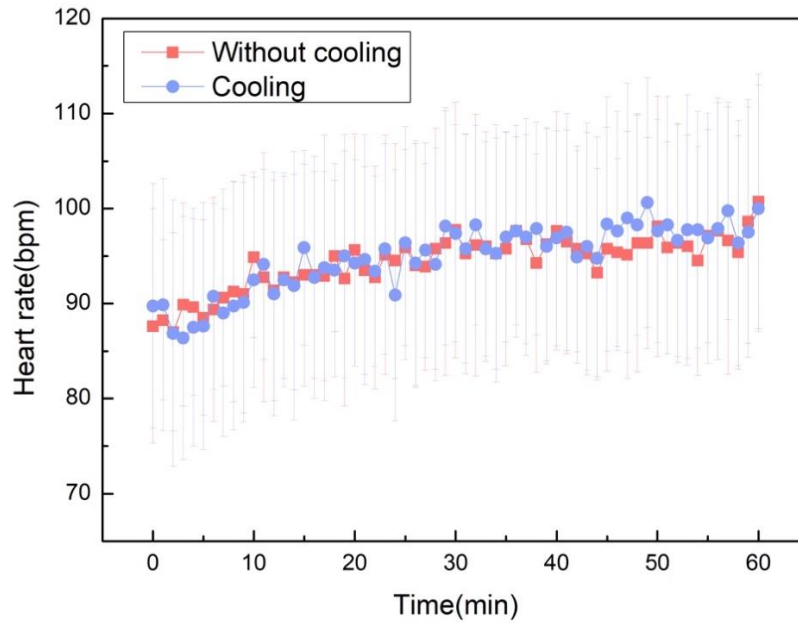
without cooling, the heart rate did not exceed 101 bpm, and there was no significant difference ( $p>0.05$ ) in the results.



(a)



(b)



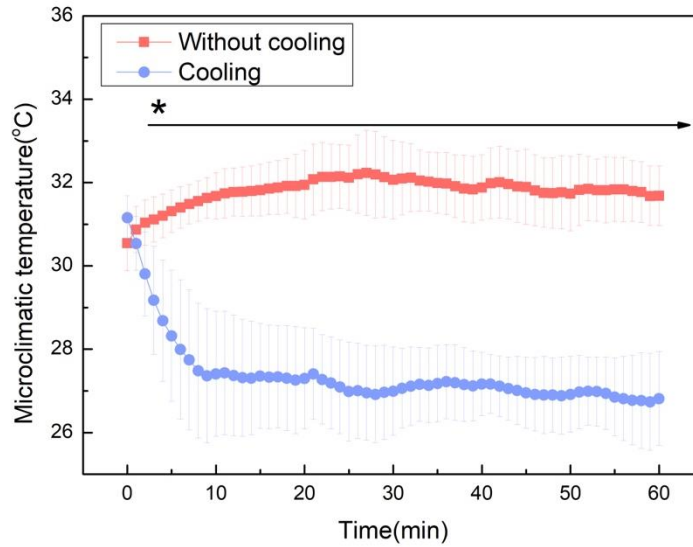
(c)

\*:  $P < 0.05$

**Figure 5.5** Comparison of changes in the core temperature (a), mean skin temperature (b) and heart rate (c) between control and cooling group.

### 5.3.2 Microclimatic temperature

A significant difference in the microclimatic temperature was observed from the 2nd minute onwards ( $p < 0.05$ ), suggesting that the WCDS has the ability to reduce the temperature within the personal protective clothing (Fig 5.6). The maximum temperature difference ( $5.3^{\circ}\text{C}$ ) of the microclimate under protective garment was recorded at the 28th minute of the experiment.



\*:  $P < 0.05$

**Figure 5. 6** Changes of microclimatic temperature in the upper back area during the whole test period.

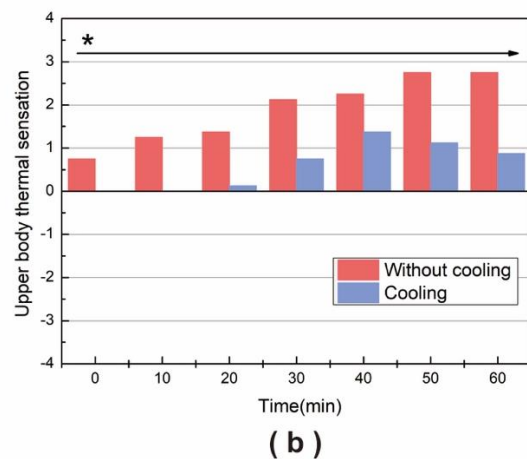
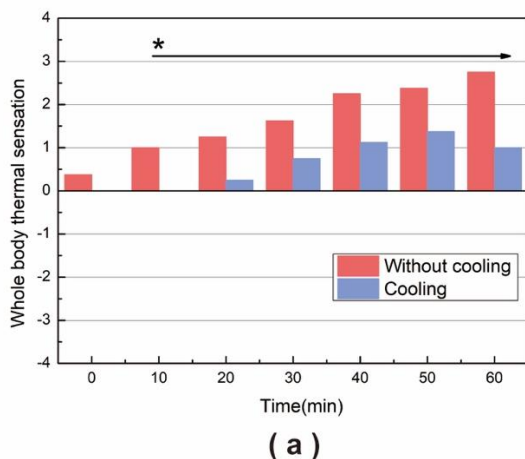
### 5.3.2 Subjective assessments

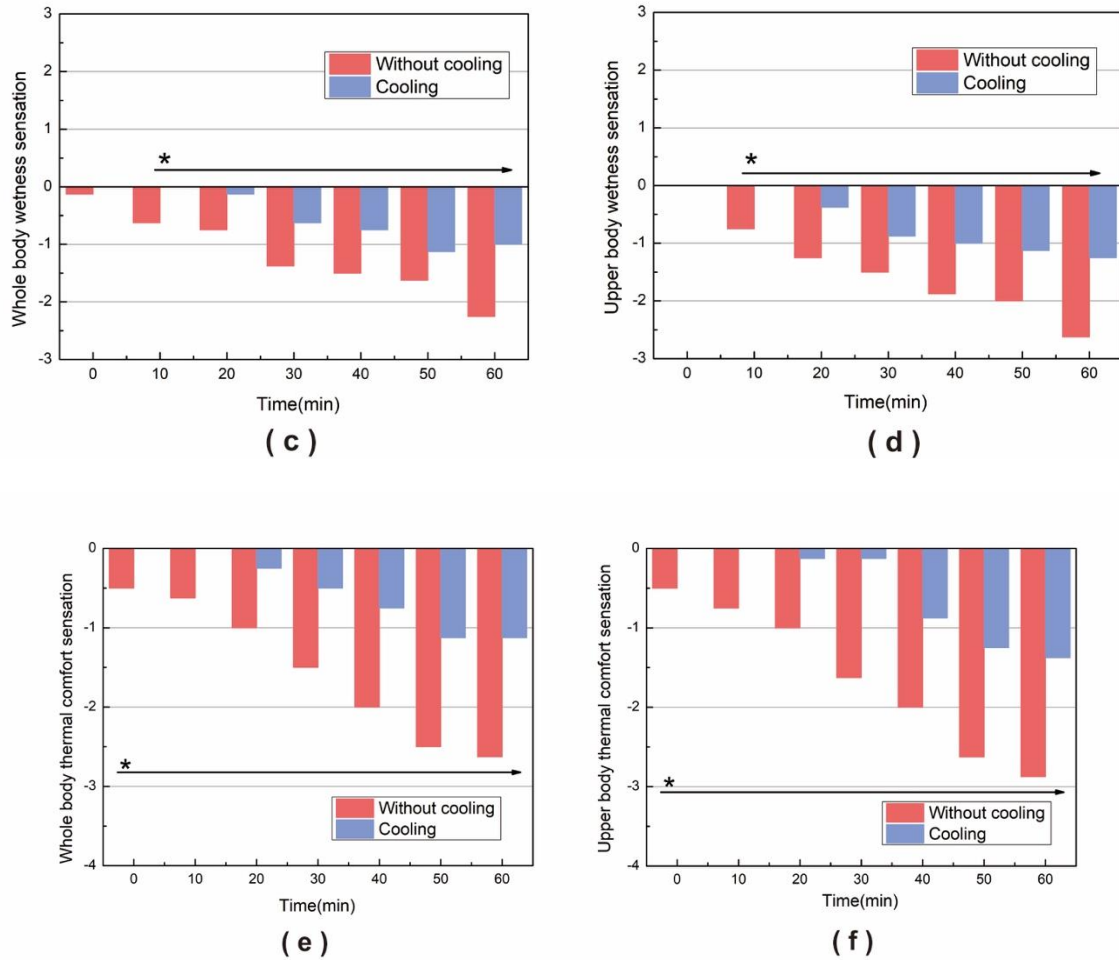
As depicted in Fig 5.7a and 5.7b, the overall and upper body thermal sensations under the cooling condition were consistently lower than those under the non-cooling condition throughout the testing period. A significant difference ( $p < 0.05$ ), ranging from 0.8 to 1.7, was observed from 10th minutes in the overall body thermal sensation between the two conditions, suggesting that the WCDS enhanced the overall body thermal sensation. A significant difference ( $p < 0.05$ ) was also noted in the upper body thermal sensation, with a disparity ranging from 0.7 to 1.8 between the two conditions.

Fig 5.7c and 5.7d illustrate that the overall and upper body wetness sensations under the cooling condition were lower than those under the non-cooling condition throughout the testing period. A significant difference ( $p < 0.05$ ) in the overall body wetness sensation was observed from 10th minutes, with a maximum difference of 1

between the two conditions. A significant difference ( $p < 0.05$ ) in the upper body wetness sensation was also observed from 10th minutes, with a maximum difference of 1.3 between the two conditions. This result proves that the cooling effect of WCDS reduced the perspiration of human subject.

The whole body thermal comfort sensation and upper body thermal comfort sensation were presented in Fig 5.7e and 5.7f, respectively. Throughout the testing period, participants reported a higher level of comfort under the cooling condition compared to the non-cooling condition, suggesting that the WCDS is an effective method to improve thermal comfort. A significant difference ( $p < 0.05$ ) was observed in both the overall body thermal comfort sensation and the upper body thermal comfort sensation between the two conditions, with a range of 0.5 to 1.5.



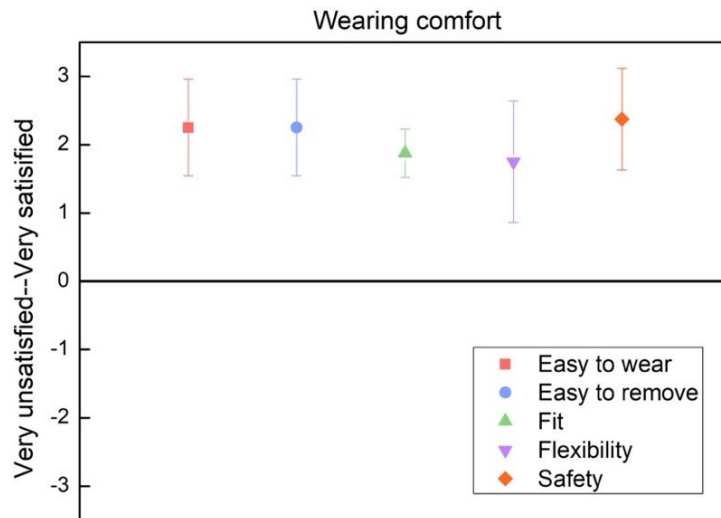


\*: P<0.05

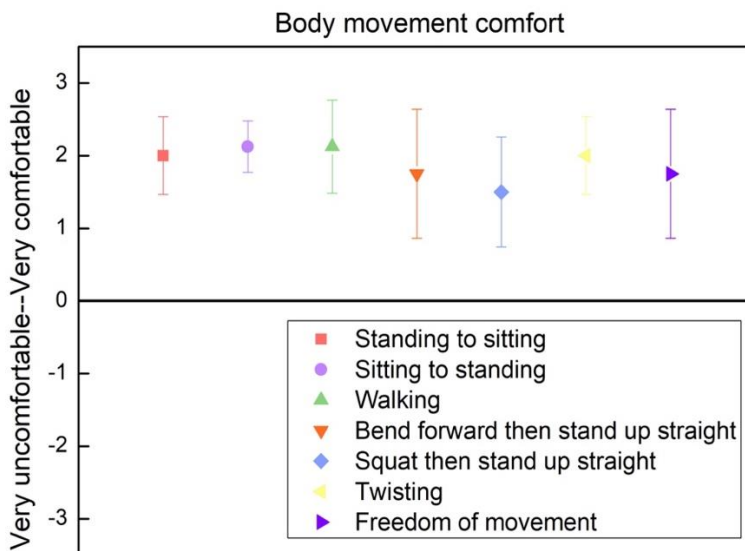
**Figure 5.7** Time changes in the whole body -, upper body - thermal sensations (a,b), wetness sensation (c,d), thermal comfort sensation (e,f) in control and cooling group.

### 5.3.3 Wearing trial results

The wearing comfort of WCDS are showed in Fig 5.8a. The data indicating a general satisfaction with its wearability. Fig 5.8b illustrates the comfort levels associated with body movement in six different postures, as well as the evaluation of freedom of movement. The participants provided relatively positive comfort ratings for the WCDS across the various postures.



(a)



(b)

**Figure 5. 8** Wearing and movement comfort votes for subjects wearing WCDS.

## 5.4. Discussion

This chapter aimed to investigate the effectiveness of a WCDS in mitigating thermal stress and enhancing comfort under protective clothing. The findings provide valuable insights into the physiological and subjective responses to the WCDS, as well as its impact on the microclimate within the protective clothing.

The physiological data revealed that the cooling intervention effectively maintained a lower core temperature throughout the exercise duration, indicating its potential to prevent excessive heat accumulation. Importantly, the heart rate remained below 101 bpm in both conditions, which may be associated with the exercise intensity [189], indicating that the WCDS did not impose additional cardiovascular strain. Mean skin temperature was more likely to be affected by the skin wetness and sweat evaporation. The air-cooling system tended to reduce the sweating rate and enhanced the ventilative heat exchange. But in this experiment, skin was covered by undergarment instead of being exposed to the cooling air, so the evaporative heat loss from skin and mean skin temperatures were not significantly different for the cooling and non-cooling groups.

The WCDS also significantly altered the microclimatic temperature within the protective clothing. This is a crucial finding, as the microclimate is a key determinant of thermal comfort [190]. Compared to a traditional air cooling system, WCDS can effectively lower the microclimatic temperature without the risk of infectious diseases caused by air cooling, which cools through air circulation from the surroundings. When compared to traditional conductive cooling garments, such as phase change material (PCM)/ice vests or liquid cooling garments, which may obstruct sweat evaporation and encourage moisture condensation, WCDS can significantly reduce the microclimate relative humidity. The significant reduction in microclimatic temperature and humidity demonstrates the WCDS's potential to enhance comfort and reduce thermal stress in real-world settings.

The subjective assessments provide compelling evidence for the psychological benefits of the WCDS. The significant improvements in overall and upper body thermal sensations, along with reduced wetness sensations, highlight the WCDS's role in enhancing wearer comfort. This is particularly relevant for healthcare workers who must wear PPE for prolonged periods, as discomfort can lead to distraction, decreased work performance, and reduced compliance with necessary protective measures.

The wearing trial results further support the practicality of the WCDS, with participants reporting general satisfaction with its wearability and movement comfort. This suggests that the WCDS can be integrated into protective clothing without significantly compromising mobility, which is critical for occupational settings.

It is important to recognize certain limitations of this laboratory study. To ensure participant safety, variables such as environmental conditions and exercise intensity were strictly controlled. A field study may provide a more realistic assessment of the cooling effect. Furthermore, the study's participants were exclusively college students, not healthcare workers. The influence of gender should also be considered in future research.

## **5.5. Conclusion**

This study provides valuable insights into the effectiveness of a WCDS in mitigating

thermal stress and enhancing comfort under protective clothing. The WCDS significantly reduced core temperature, improved thermal sensation, and reduced wetness sensation compared to the non-cooling condition, without imposing additional cardiovascular strain or compromising mobility. The wearing trial results indicated a general satisfaction with the wearability and movement comfort of the WCDS. This suggests that the WCDS can be integrated into protective clothing without significantly compromising mobility, which is critical for occupational settings.

In conclusion, the WCDS appears to be a promising strategy for mitigating thermal stress and enhancing comfort under protective clothing. Future research should explore the long-term effects of the WCDS and its applicability in various occupational and clinical settings. The findings of this study have important implications for the design of protective clothing and the development of strategies to enhance comfort and safety for personal protective clothing.

# **Chapter 6 Development of a Personal Cooling Garment for Hot Environment**

## **6.1 Introduction**

Heat stress is a significant occupational hazard for workers engaged in physically demanding activities, particularly in hot ambient environments. Outdoor workers, such as those in construction, agriculture, and mining industries, are at a heightened risk of heat stress due to their direct exposure to sunlight during summer months [191-193]. When the body's heat dissipation mechanisms, including evaporation, conduction, convection, and radiation, fail to balance the heat generated during work, heat accumulates within the body, increasing the occurrence of heat exhaustion and related illnesses [8, 194-196]. To mitigate the risks associated with heat stress and ensure optimal work performance, various personal thermal management strategies have been developed to alleviate heat strain for occupational workers in outdoor hot environments.

Personal cooling garments (PCGs) as an effective solution to lower the body temperature can potentially reduce the risk of heat-related illnesses among occupational workers [16, 18, 179]. Different types of PCGs have been reported and investigated in previous research, including air cooling garments[40, 197-199], phase change material (PCM) cooling garments [51, 53, 200], and liquid cooling garments [57, 84, 85, 201]. However, each type of PCG has its limitations. Cooling garments with PCM packs may interfere with sweat evaporation [202], cause discomfort due to localized low

temperatures [203], and even result in physical burden when the heavier weight of phase change materials is applied for a longer cooling period [53] [204]. Liquid cooling garments require extra pumps, compressors, and a sufficient volume of cooling liquid, leading to inconvenience and increased weight [57]. Additionally, water condensation in liquid cooling garments can cause an uncomfortable wetness sensation for the wearer [179].

To address the above limitations, this chapter proposes a lightweight ventilation cooling garment with a novel design to provide an effective and comfortable personal cooling for outdoor workers exposed to hot environments. In this chapter, we will briefly discuss the design process of developing a new ventilation cooling garment. The design process will include analyzing the specific needs of the target user group and their working environment, exploring various cooling technologies and materials to select the most suitable approach, optimizing the garment's components, materials, and overall structure through technical drawings and prototypes, fabricating functional prototypes and planning the testing protocol to assess performance, durability, and user acceptance.

## **6.2 Design considerations**

When designing a personal cooling garment for occupational workers in hot environments, several key factors must be considered to ensure the garment's

effectiveness, comfort, and practicality.

### **6.2.1 Target user group and their specific needs**

The target user group for the personal cooling garment consists of outdoor workers in industries such as construction, agriculture, and mining. These workers are exposed to direct sunlight and high ambient temperatures during summer months, putting them at a heightened risk of heat stress and related illnesses. The cooling garment must be designed to meet their specific needs, including:

- 1). Effective cooling to prevent heat accumulation in the body.
- 2). Comfort and ease of movement to minimize interference with work tasks.
- 3). Durability to withstand the demands of physical labor and outdoor conditions.
- 4). Lightweight design to avoid adding excessive physical burden.

### **6.2.2 Environmental factors and temperature range**

The cooling garment must be designed to function effectively in the range of temperatures and humidity levels typically encountered by outdoor workers in hot environments. The garment should be able to provide sufficient cooling even in high ambient temperatures and high relative humidity conditions, where the effectiveness of some cooling methods may be limited.

### **6.2.3 Cooling mechanisms and technologies**

Various cooling technologies, such as evaporative cooling, thermoelectric cooling, phase change materials (PCMs), and air circulation and ventilation, should be evaluated for their suitability in the design of the personal cooling garment for occupational workers in hot environment. The selected cooling mechanism should be capable of providing adequate cooling power while minimizing the drawbacks associated with existing technologies, such as moisture condensation on the skin or increased weight due to heavy components.

### **6.2.4 Ergonomics and user comfort**

The cooling garment must be designed with ergonomics and user comfort in mind. The garment should allow for ease of movement and flexibility, ensuring that it does not hinder the wearer's ability to perform their work tasks. The placement of cooling components and the distribution of weight should be carefully considered to minimize discomfort and physical burden.

### **6.2.5 Durability and maintenance requirements**

Given the demanding nature of outdoor work environments, the cooling garment must be constructed using durable materials that can withstand regular use and exposure to the elements. The garment should be easy to clean and maintain, with a focus on minimizing downtime and ensuring a long product lifespan.

## **6.3 Conceptual design**

### **6.3.1 Brainstorming and ideation process**

To generate innovative ideas for the cooling garment design, a brainstorming session was conducted with a diverse team of experts, including designers, engineers and end-users. The team focused on identifying novel solutions that address the limitations of existing cooling garments while prioritizing user comfort, effectiveness, and practicality.

During the ideation process, the following key aspects were considered:

- 1) Maximizing cooling efficiency while minimizing weight and bulk
- 2) Enhancing user comfort by improving moisture management and thermal distribution
- 3) Ensuring compatibility with existing work environments
- 4) Exploring sustainable and eco-friendly materials and technologies

### **6.3.2 Evaluation of existing cooling technologies**

Several cooling technologies were evaluated for their potential application in the lightweight ventilation cooling garment. The most possible technologies will be discussed in the following section.

### **6.3.2.1 Evaporative cooling**

Evaporative cooling relies on the principle of heat absorption during the evaporation of water. While this method can be effective in low-humidity environments, its performance may be limited in high-humidity conditions where evaporation is hindered. Additionally, evaporative cooling can lead to increased moisture buildup within the garment, potentially causing discomfort for the wearer.

### **6.3.2.2 Thermoelectric cooling**

Thermoelectric cooling utilizes the Peltier effect to create a temperature difference between two surfaces of a thermoelectric module when an electric current is applied. Although this technology can provide localized cooling, it requires a relatively large power source and may not be suitable for prolonged use in outdoor environments. Furthermore, our previous research indicated that TE modules exhibit reduced cooling efficiency when operating in hot environments, limiting their practical application for outdoor workers.

### **6.3.2.3 Phase change materials (PCMs)**

PCMs absorb and release heat during their phase transition, providing a cooling effect. While PCMs can be effective in managing heat, they have limitations such as added weight and potential discomfort due to localized cold spots. Furthermore, the PCMs need to be placed close to the skin surface and the moisture condensation on the surface of PCM packs can lead to increased skin wetness, causing discomfort for the wearer.

#### **6.3.2.4 Air circulation and ventilation**

Air circulation and ventilation can enhance cooling by promoting evaporation and convective heat transfer. By incorporating fans or ventilation channels into the garment design, hot and humid air can be replaced with cooler, drier air. However, the effectiveness of this method may be limited in high ambient temperatures, and the direct airflow on the skin surface may cause discomfort.

#### **6.3.3 Selection of the most suitable cooling technology**

Compared with other types of cooling garment, air cooling garments (ACGs) which take advantage of sweating evaporation during forced convection and avoid moisture condensation can potentially provide a more comfort cooling effect in hot environments [205]. Previous research [40, 197, 198, 206] found that ACGs can offer improved wetness sensation, significant body temperature drop, and longer cooling durations. However, their effectiveness can be limited in the conditions with high ambient temperature and high relative humidity [205, 207]. To meet the cooling requirements of occupational workers in high-temperature environments, hybrid ventilative cooling garments have been developed. Al Sayed et al. [33] developed an Air/CO<sub>2</sub> cooling garment, which can create a cool microclimate with an average temperature of 12.5 ( $\pm 0.4$ ) °C beneath the garment; however, its two cylinders, which contain 1.36 kg of two-phase CO<sub>2</sub>, result in a total weight of 5.1 kg that increases physical burden. In Wu et al. [80]'s research, pressurized air was supplied to a ventilative cooling vest for an

enhanced cooling effect. Temperature of the cooling air was between 29 and 31 °C, but the additional air compressor inevitably limits the portability of the garment system. Chan et al. [208] designed a cooling vest that combined PCM and electric fans to improve the air cooling effect; however, the system was only effective for the rest period between exercise bouts, due to the limited cooling power of PCM. Song et al. [209] also combined electric fans with PCM for hot environments cooling and found that this garment system could improve the local- and whole-body thermal comfort. However, water condensation was found on the surface of the PCM packs, which may directly contact the skin and increase skin wetness, this phenomenon was also observed in Chan et al. [208]'s research. Therefore, the insufficient cooling, heavy weight components and moisture condensation on skin are major problems for existing hybrid air cooling systems.

To address the above limitations, this chapter proposes a lightweight ventilation cooling garment with a novel design to provide an effective and comfortable personal cooling for outdoor workers exposed to hot environments. The new design aims to overcome the impact of ambient temperature on cooling efficiency and to avoid thermal discomfort caused by the direct contact between PCMs and skin.

## **6.4 Preliminary design**

The new designed cooling garment consists of three primary components: a basic vest,

a cooling unit, and a cooling source. The cooling system features a novel design that effectively extract heat from the microclimate regions of the clothing system through a combination of conductive and convective heat transfer.

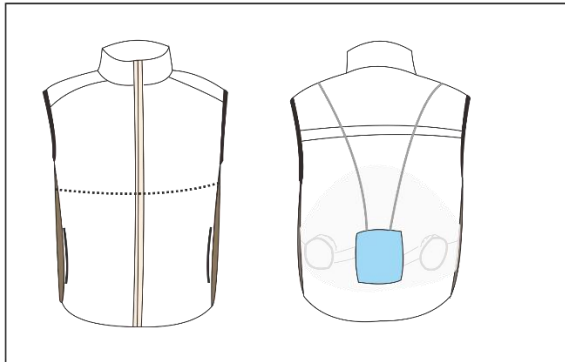
#### **6.4.1 Garment pattern design**

Since our new cooling garment design is similar to the traditional air cooling garment, we initially decided to use the pattern of the traditional air cooling garment as a reference, as illustrated in Figure 6.1a. The first prototype consists of a two-layer vest with a front zipper for easy wearing and removal. A pocket is sewn onto the lower back of the vest, designed to hold a plastic bag that can be filled with ice or cold water to provide cooling. This pocket features a square-shaped structure that can be securely sealed from the top to prevent leakage. To ensure the vest can support the weight of the cooling system, both inner and outer buckle belts with Velcro fastenings are incorporated, allowing for adjustable fit and stability. Additionally, a separate pocket is included on the front of the vest to accommodate the battery required for the cooling system.

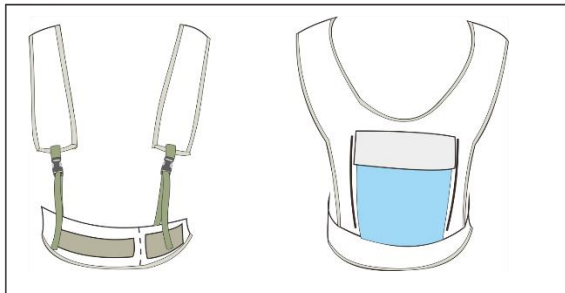
We also designed a second prototype, as shown in Figure 6.1b, which takes advantage of our previous design for the WCDS. This new design consists of four main components: a shoulder strap to help distribute and support the weight of the entire cooling system; an inner section at the lower back specifically designed to hold the cooling unit; an outer section at the lower back, which serves as a pocket for the cooling

source; and three adjustable buckles located at the front and on both sides of the vest to ensure a secure and comfortable fit for users of different body sizes. The cooling source container, sewn onto the lower back of the vest, is designed to hold a plastic bag that can be filled with ice, cold water, or other cooling materials as needed.

a)



b)



**Figure 6. 1** Schematic design of the basic vest. a) Prototype 1. b). Prototype 2.

#### **6.4.2 Garment material selection**

To better simulate real-world user scenarios, particularly outdoor summer conditions, we initially selected nylon as the outer layer for Prototype 1. This choice was based on two primary considerations: first, to minimize air exchange between the interior and exterior of the garment, thereby enhancing the cooling efficiency; and second, to provide protection against ultraviolet (UV) radiation. Nylon is characterized by its

relatively low air permeability while remaining breathable, and it is capable of absorbing UV radiation within the wavelength range of 280–400 nm. To further optimize user comfort and facilitate effective air distribution, we adopted a two-layer garment structure. An elastic mesh fabric was chosen for the inner lining to improve ventilation and reduce potential discomfort associated with direct contact with the cooling system. However, during the initial design phase, it became apparent that the nylon fabric alone was too lightweight to adequately support the weight of the entire cooling system. To address this, we incorporated Velcro fasteners and buckle belts, which not only provided additional structural support but also allowed the cooling system to be easily attached to or detached from the garment. As illustrated in Figure 6.2a, the first prototype was constructed using nylon fabric and the initial pattern design.

Following user trials, several limitations of the first prototype were identified. Participants reported that the nylon fabric was too light and soft to reliably support the cooling system, leading to issues with fit and stability. Additionally, the lack of waterproofing in the nylon fabric resulted in increased skin wetness due to condensation or leakage from the cooling source, which could compromise user comfort and safety. In response to these findings, we sought alternative materials that could address these shortcomings. We subsequently identified a waterproof nylon fabric that offered enhanced strength and durability, making it suitable for supporting the weight of the cooling system while also preventing water leakage. Utilizing this improved material, we developed a second garment prototype based on the revised pattern design (Pattern

Design 2), as shown in Figure 6.2b.

a)



b)

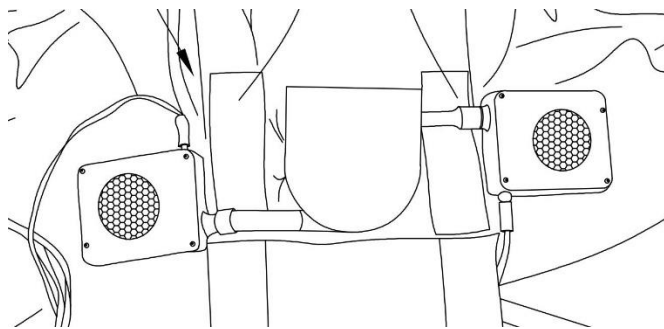


**Figure 6. 2** Two prototypes with different materials.

### 6.4.3 Cooling system design

Based on the design of the wearable cooling and dehumidifying system [81], the cooling unit consists of two blowers and a heat exchange chamber. In our initial prototype, these components were simply connected using tubes and then attached to the garment with Velcro, as illustrated in Figure 6.3. Inside the chamber, the air stream undergoes convective heat exchange with aluminum fins arranged in a spiral pattern, based on our previous work [81], to optimize heat transfer efficiency within a limited space. However, through further evaluation, we determined that high-speed blowers, as

used in previous designs, were not necessary for effective operation. Following an online investigation and performance analysis, we opted to replace the high-speed blowers with lower-speed alternatives. This adjustment not only improved the overall performance of the system but also significantly reduced the weight of the entire cooling unit, thereby enhancing user comfort and wearability.



**Figure 6. 3** Schematic design of the first prototype of the cooling unit.

## **6.5 Improved design**

As discussed in Section 6.4, we explored various patterns and materials for the newly designed cooling garment. Building on these initial trials, we subsequently focused on optimizing the overall design to enhance the garment's performance, comfort, and usability.

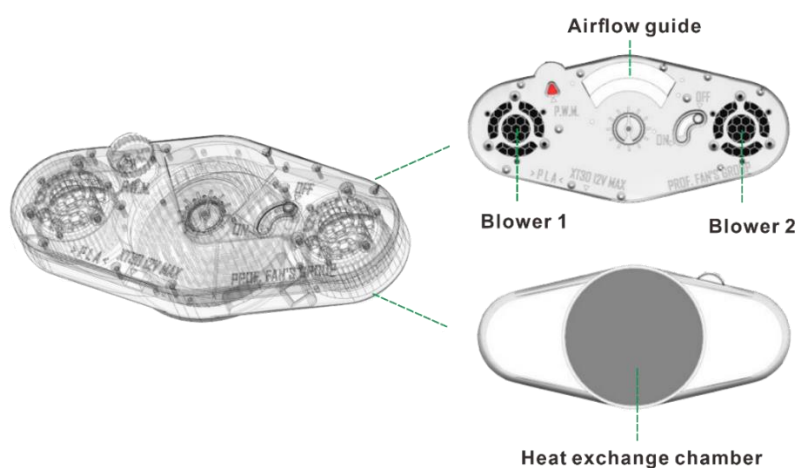
### **6.5.1 Improved cooling unit design**

In the previous design, as shown in Figure 6.3, the components were simply connected using tubes, resulting in a configuration that was not suitable for practical use. To address this limitation, we sought to redesign the cooling system as a single integrated

unit. Accordingly, we developed and evaluated two different prototypes, as described below.

### First prototype

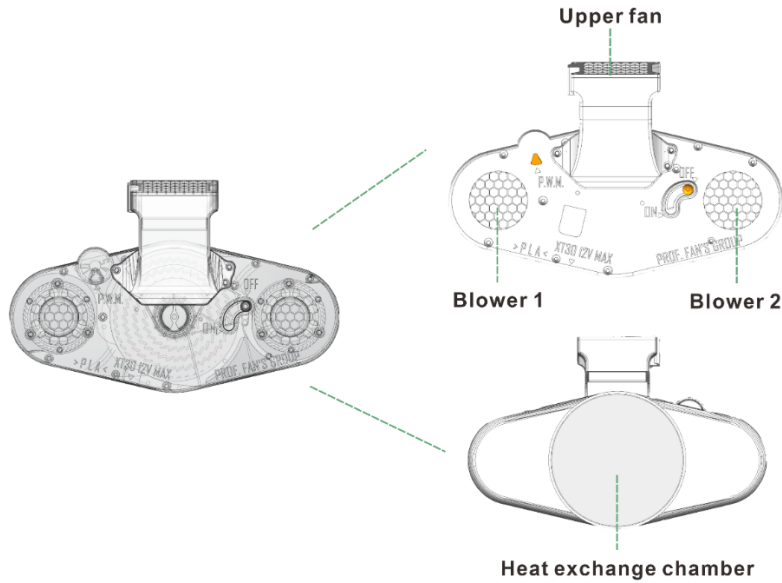
As shown in Fig 6.4, cold air is generated by the cooling unit and distributed to different microclimate regions in the clothing through an airflow guide. The cooling source (a pack of ice water) is attached to the cooling unit. The heat exchange chamber directly contacts with the cooling source and is made of aluminum alloy to guarantee a high thermal conductivity. Micro-blowers (blower 1 and 2) pump air from the clothing microclimate regions into the heat exchange chamber from the left and right sides. After the air is cooled in the heat exchange chamber, the cold air will be distributed to different microclimate regions in the clothing through an airflow guide. Both the heat change chamber and the cooling source don't contact the human body, and therefore avoid increasing skin wetness during the cooling process.



**Figure 6. 4** Schematic design of the first prototype of the improved cooling unit.

## **Second prototype**

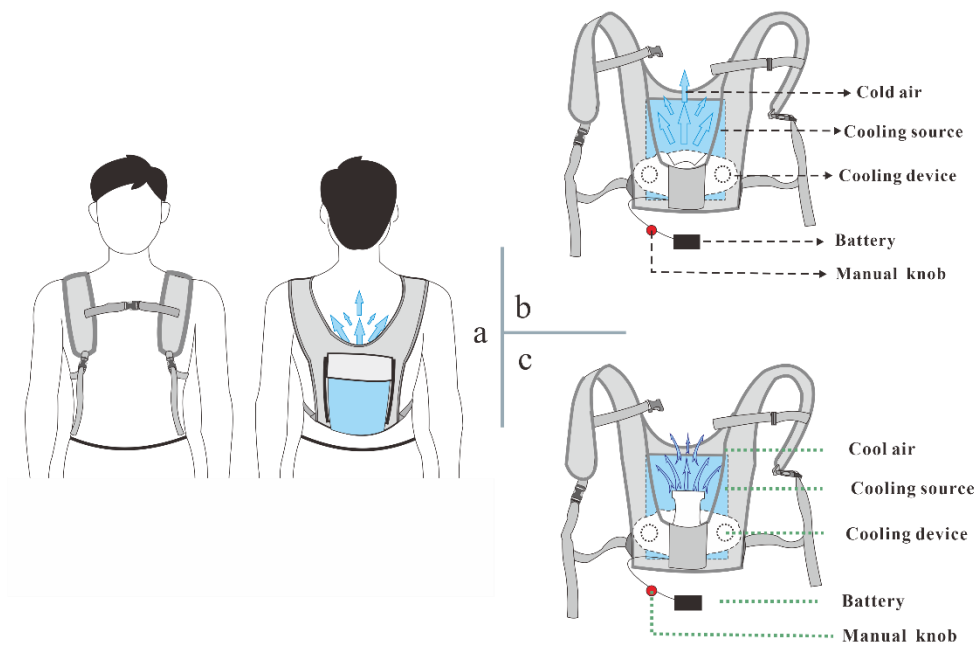
Based on the design of cooling unit prototype 1, we add an additional fan on the top to accelerate the airflow rate and spreads the cool air throughout the clothing microclimate. As shown in Fig 6.5, similar with prototype 1, cold air is still generated by the cooling unit and then distributed to different microclimate regions in the clothing through the top fan. The prototype 2 comprises a heat exchange chamber, a pair of micro-blowers (blower 1 and 2), and a fan which positioned at the upper side of the first air outlet (air outlet 1). Micro-blowers (blower 1 and 2) pump air from the clothing microclimate regions into the heat exchange chamber from the left and right sides. After the air is cooled in the heat exchange chamber, upper fan accelerates the airflow cooled by the cooling source and distributes the cool air to different microclimate regions in the clothing through an airflow guide. Both the heat change chamber and the cooling source don't contact the human body, and therefore avoid increasing skin wetness during the cooling process.



**Figure 6. 5** Schematic design of the second prototype of the cooling unit.

### 6.5.2 Improved garment design

We simplified the second garment design to enhance its compatibility with the cooling system and to improve overall wearability. This streamlined approach ensures that the garment integrates more effectively with the cooling components while providing greater comfort and ease of use for the wearer. As shown in Fig 6.6, the cooling vest comprises four parts: a shoulder strap to support the weight of the entire cooling system, an inside part of the lower back to hold the cooling unit, an outside part of the lower back (a pocket) to hold the cooling source, and three adjustable buckles in the front and on both sides of the vest for a better fit. The pocket (cooling source container) is sewn onto the lower back of the vest and contains a plastic bag that can hold ice, cold water, or other cooling sources.



**Figure 6.6** a). Schematic design of the cooling vest (front and back view). b). Inside view with cooling unit prototype 1. c). Inside view with cooling unit prototype 2.

### 6.5.3 Final selection of materials

To ensure comfort, usability, and breathability, a double-layer mesh fabric with spacer fabric in between was chosen for the shoulder straps to support the weight of the entire cooling system. For the lower back part and pocket, a wear-resistant layer of waterproof nylon fabric was used to reduce the wetness sensation caused by water condensation.

The heat exchange chamber is made of aluminum alloy (AlSi10Mg) through Selective Laser Melting 3D printing, followed by a 300°C heat treatment. Then the aluminum part undergoes a surface treatment through anodizing to improve corrosion resistance.

[81] The outer shell of the cooling unit, which features two air outlet for cooling air

distribution, is fabricated through 3D printing using polylactic acid. The micro-blowers (blower1 and 2) were selected from Sunon Inc (Model PF 60251VX-C01C-GA9), the upper fan was selected from Asia Vital Components Co.,Ltd (Model DYTb 0420B2S).

The cooling source is a square container consisting of a pocket sewn onto the lower back of the vest and a plastic bag placed inside the pocket. Ice packs or other cooling sources can be added to the plastic bag, sealed, and embedded in this pocket. Additionally, an insulation layer is placed outside the pocket to reduce heat exchange between the cooling source and the environment, minimizing energy loss.

## **6.5.4 Ergonomic considerations**

### **Placement of cooling components**

The cooling unit is placed inside the cooling vest on the lower back, accessible through a zipper beside the pocket. The cold air outlet's position was chosen based on previous investigations of optimal cooling positions [210, 211] and heat distribution across the human body [212, 213].

### **Weight distribution and balance**

The cooling unit, cooling packs, and manual knob are integrated into the vest, resulting in a total weight of 0.42kg for prototype 1 and 0.47 kg for prototype 2. The battery is placed in the front pockets to power the blowers, helping to balance the weight distribution of the cooling system.

### **Flexibility and range of motion**

The entire cooling system is detachable from the vest, allowing for flexibility and a full range of motion when the cooling function is not required.

## **6.6 Prototype development**

Based on the detailed design specifications, two functional prototypes of the cooling garment were created. The prototypes incorporated the selected fabrics, garment construction, and cooling system components. The cooling vest was constructed with the chosen fabrics, and the cooling system components were integrated into the garment as per the design. And then the functional prototypes underwent a series of iterative refinements and optimizations to improve its performance and user experience. The cooling system's efficiency was evaluated, and adjustments were made to the heat exchange chamber's design, the blowers' positioning, and the airflow distribution. The garment's fit and comfort were also assessed, leading to modifications in the sizing, adjustability features, and the placement of cooling components. These refinements aimed to enhance the cooling performance, ergonomics, and overall functionality of the cooling garment.

## **6.7 Performance evaluation and testing**

To assess the effectiveness and performance of the new designed ventilation cooling

garment, a series of evaluations and tests will be conducted. The testing protocol will be designed to examine the garment's cooling capacity, thermal comfort, ergonomics, and durability under hot environment.

### **Thermal manikin testing**

Thermal manikin tests will be performed to evaluate the cooling garment's heat extraction capabilities. The manikin will be dressed in the new designed cooling garment and exposed to hot environments. The detailed testing protocol will be explained in Chapter 7.

### **Human subject testing**

After the thermal manikin test, the best cooling performance setting will be chosen for human trial. Human subject testing will be conducted to evaluate the cooling garment's effectiveness in real-world scenarios. Participants will be recruited to wear the cooling garment while performing physical activities in controlled environmental chambers. The physical and psychological evaluation will be conducted during the testing. The detailed discussion will be provided in Chapter 8.

### **Data analysis and performance evaluation**

The data collected from the thermal manikin tests, human subject testing, and comparative evaluations will be analyzed using appropriate statistical methods to quantify the cooling garment's performance. Key evaluation parameters, including

cooling power will be collected from the thermal manikin tests. Physiological results, such as core temperature, skin temperature and heart rate, along with psychological results, including thermal sensation, thermal comfort, and perceived exertion, will be analyzed to provide a comprehensive assessment of the garment's effectiveness in human trials. The results of the data analysis will be used to identify areas for further improvement, validate the cooling garment's design and functionality, and establish its potential for real-world applications.

# **Chapter 7 Evaluation of Ventilation Cooling Garment Through Sweating Thermal Manikin**

## **7.1 Introduction**

This chapter focuses on evaluating the newly developed ventilation cooling garment (VCG) using a thermal manikin. Thermal manikins are essential tools for assessing the cooling performance of personal cooling garments, providing reliable and repeatable measurements under controlled environmental conditions. The primary objectives of this thermal manikin study are to assess the cooling performance of the VCG under hot environmental conditions, compare the cooling effectiveness of the VCG with a commercial air cooling garment (ACG) under different cooling system settings, provide insights into the garment's cooling power and optimal air flow rates, investigate the water loss rates associated with the use of the VCG and ACG, and analyze the air outlet temperature profiles of the VCG under its best cooling power setting condition.

The findings from this study will contribute to the overall understanding of the ventilation cooling garment's performance, validate the design choices made during its development, and guide further refinements and optimizations to enhance the garment's effectiveness and user experience. The test protocols and data analysis will be discussed in the following sections and the results will provide valuable information for the development of future personal cooling garments and their applications in various industries.

## **7.2 Method**

### **Test condition and equipment**

The study was conducted in a climatic chamber set to 35°C, 50% relative humidity, and an air velocity of 0.1 m/s, simulating outdoor summer conditions. A perspiring thermal manikin, Walter, was used to evaluate the cooling performance of the VCG [137]. The manikin was dressed in the cooling vest, with an undervest worn inside and a UV protection jacket worn outside. The manikin's skin temperature was set to a constant 35°C to simulate a realistic clothing microclimate.

### **Cooling garments and test protocols**

The VCG was tested under three different air flow rates based on the speed of micro - blowers (blowers 1 and 2), which provided the same input power and served as the start of the cooling mechanism. The input power of upper fan were fixed theoretically for better cooling performance [31]. For comparative analysis, a commercial air cooling Garment (ACG) was also tested under corresponding air flow rate conditions. Furthermore, to gain a more comprehensive understanding of the cooling performance provided by different blowers, the VCG was tested without a cooling source (utilizing only upper fan).

The average cooling power of the VCG was calculated as the difference between the power input to the manikin using the cooling garment with different air flow rates (L, M, and H). After achieving thermal equilibrium, a 7.5-hour test was conducted for

cooling testing and data collection. The cooling source was replaced every 1.5 hours to maintain consistency with subsequent human subject tests.

All manikin tests were conducted in a climate chamber with precisely controlled environmental conditions to ensure reliable results.



**Figure 7. 1** Perspiring thermal manikin-Walter in testing condition.

### **7.3 Results and discussion**

We measured the air flow rate of prototypes 1 and 2 under three different settings based on the speed of micro-blowers (blowers 1 and 2), which provided the same input power (0.5 W, 1.5 W, and 6 W) and served as the crucial cooling components of the cooling mechanism. As shown in Table 7.1, the upper fan significantly increased the air flow rate in prototype 2 compared to prototype 1, particularly at low and medium speeds.

**Table 7. 1** Air flow rate of air outlet for different prototype under three different settings.

Air flow rate (L/min)	Prototype 1	Prototype 2
Low speed (L)	13	91
Medium speed (M)	26	91
High speed (H)	88	92

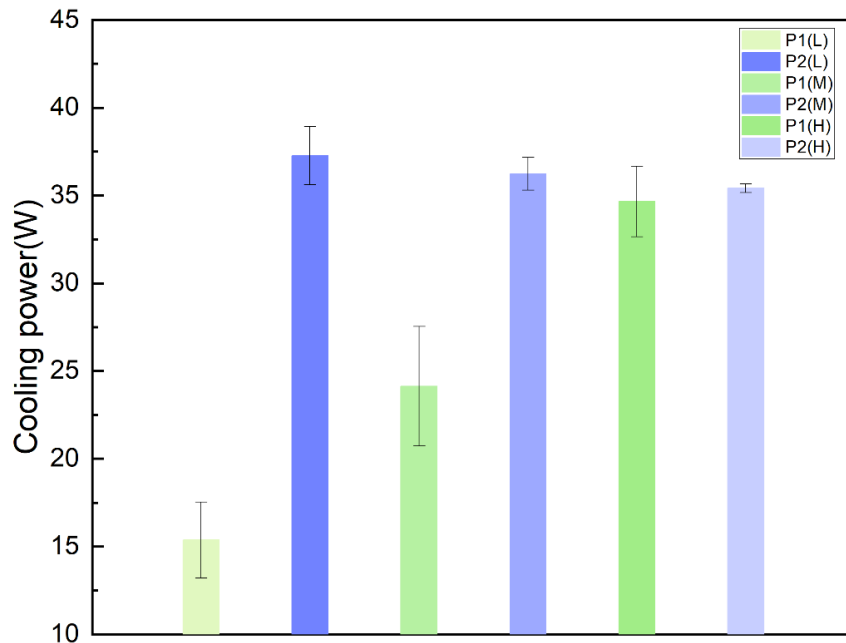
### 7.3.1 Cooling power comparison

The cooling performance of the newly designed ventilation cooling garment (VCG) was evaluated in comparison with a commercial air cooling garment (ACG) under three different airflow rates designated as low (L), medium (M), and high (H).

#### 7.3.1.1 Prototype 1 and prototype 2

Figure 7.2 presents a comparative analysis of the cooling power between two prototype ventilation cooling garments, labeled as P1 and P2, under different blower speed settings in the heat exchange chamber (L, M, and H). The cooling power of P1 increases as the blower speed is elevated from L to M and H, while P2 shows the opposite trend. However, P2 consistently outperforms P1 in terms of cooling power across all blower speed settings, with the performance advantage being most pronounced at the lowest blower speed setting (L). At this level, P1 exhibits the lowest cooling power, averaging around 15 W, while P2 achieves approximately 37 W, indicating that P2 delivers more than twice the cooling power of P1. This finding suggests that the design optimizations incorporated in P2 are particularly effective at lower air flow rates, enabling it to achieve significant cooling power while operating at a lower blower speed. The lower

speed can provide a relatively higher heat transfer efficiency between the cooling unit and the cooling source, potentially due to increased contact time between the air and the cooling surfaces. As the fan speed increases to M and H, the cooling performance gap between P1 and P2 narrows, indicating that the benefits of P2's design optimizations diminish at higher air flow rates. Operating P2 at lower fan speeds can provide optimal cooling performance while potentially minimizing energy consumption and noise levels, offering a more efficient and user-friendly solution compared to P1.



P1: Prototype 1; P2: Prototype 2.

**Figure 7. 2** Cooling power comparison of prototype 1 with 2.

### 7.3.1.2 Prototype 2 and commercial air cooling garment

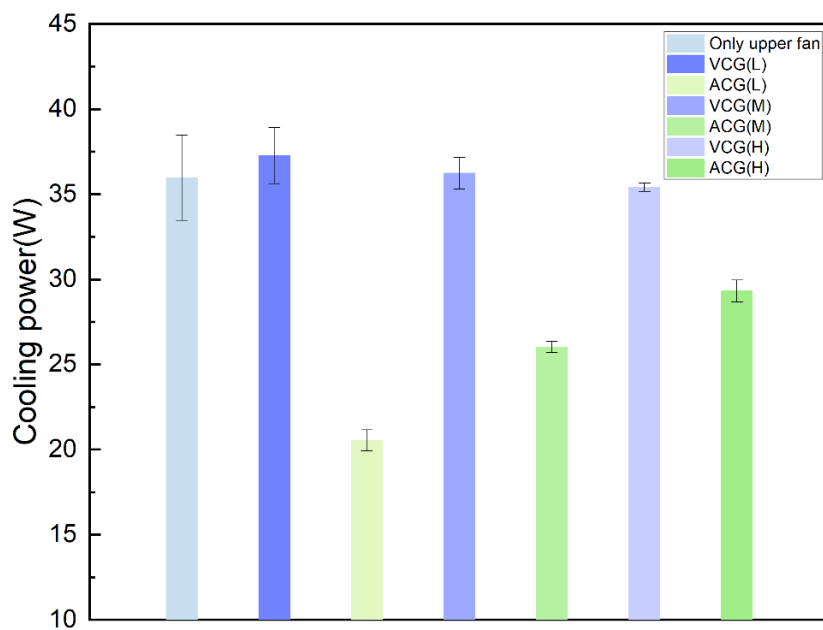
As shown in Figure 7.3, the VCG consistently demonstrated superior cooling power

across all test conditions. At the low airflow rate (L), the VCG delivered approximately 37W of cooling power, while the ACG produced only about 20W under the same conditions. This substantial difference in performance (approximately 85% higher) indicates that the VCG design is particularly effective at lower airflow settings within the heat exchange chamber. As airflow rates increased to medium (M) and high (H) levels, the VCG maintained relatively stable cooling power (approximately 36W and 35W, respectively), whereas the ACG showed progressive improvement (26W at M and 29W at H).

The measurement using only the upper fan with the same cooling source (ice) generated approximately 35.5W of cooling power. This reference point helps quantify the additional cooling contribution provided by the design of the cooling device, which initially cools the air through two blowers and then accelerates it using the upper fan. This highlights the significant thermal enhancement achieved by the VCG design.

The observed performance pattern suggests that the VCG's cooling efficiency is less dependent on airflow rate compared to the commercial alternative. This characteristic may be attributed to the optimized heat exchange configuration in the VCG, which allows for more effective thermal exchange at lower airflow rates. The inverse relationship between airflow rate and cooling performance in the VCG indicates that operating at lower fan speeds (L) may provide optimal cooling efficiency while potentially reducing energy consumption.

These findings have important implications for the design and operation of personal cooling garments. The VCG's ability to maintain high cooling power at lower airflow rates suggests opportunities for energy-efficient cooling solutions that could benefit various applications requiring personal thermal management. By taking advantages of the VCG's design principles, it may be possible to develop more efficient and effective personal cooling systems that optimize thermal comfort while minimizing energy consumption.



**Figure 7. 3** Cooling power comparison of the ventilation cooling garment (VCG) with the commercial air cooling garment (ACG).

## 7.4 Conclusion

The thermal manikin study provided valuable insights into the performance of the

newly designed Ventilated Cooling Garment (VCG) prototypes (P1 and P2) and their comparison with a commercial Air Cooling Garment (ACG). The study evaluated the cooling power of the two prototype VCGs and found that P2 consistently outperformed P1, particularly at lower blower speed settings. This finding suggests that the design optimizations incorporated in P2 are especially effective at lower air flow rates, enabling it to achieve substantial cooling power while operating at a lower blower speed, potentially leading to increased heat transfer efficiency and reduced energy consumption.

Furthermore, the comparison between the VCG (P2) and the commercial ACG revealed that the VCG consistently demonstrated superior cooling power across all test conditions. At low airflow rates, the VCG delivered approximately 85% higher cooling power than the ACG. The VCG maintained relatively stable cooling power as airflow rates increased, while the ACG showed progressive improvement. The reference point measurement using only the upper fan with the same cooling source highlighted the significant thermal enhancement achieved by the VCG design, which initially cools the air through two blowers and then accelerates it using the upper fan. The inverse relationship between airflow rate and cooling performance in the VCG indicates that operating at lower fan speeds may provide optimal cooling efficiency while potentially reducing energy consumption.

In conclusion, this study demonstrates the superior performance and efficiency of the

newly designed VCG compared to a commercial ACG. The findings highlight the potential for optimized personal cooling systems that can achieve significant cooling power at lower airflow rates, leading to reduced energy consumption and improved user comfort. With further optimizations, the VCG has the potential to become a leading solution for alleviating heat stress and improving thermal comfort in a wide range of applications. Future studies should also investigate the long-term durability, user comfort, and practical application of the VCG in various industrial, sports, and military settings.

# **Chapter 8 Performance Investigation of Ventilation Cooling Garment Through Human Subject Testing**

## **8.1 Introduction**

This chapter investigates the real-world performance of our newly developed ventilation cooling garment through human subject testing. While thermal manikin testing provided valuable quantitative data on cooling power properties under controlled conditions, such testing cannot capture the complex physiological and psychological responses of human wearers. The human body's sophisticated thermoregulatory system interacts with cooling garments cannot be fully simulated by thermal manikins. Additionally, subjective perceptions of comfort, mobility restrictions, and overall wearability significantly influence a cooling garment's practical utility and user acceptance.

The primary objectives of this human subject investigation were 1) to quantify the garment's cooling performance under realistic environmental conditions and physical activities; 2) to measure the impact of the cooling system on wearers' physiological responses and thermal comfort perception; 3) to evaluate the garment's ergonomic properties, usability, and overall user experience during varied movement patterns.

This human-centered evaluation combining objective physiological measurements with subjective assessments of thermal sensation, comfort, and movement comfort. By

analyzing these data, we provide a comprehensive understanding of the garment's effectiveness that bridges the gap between technical performance and practical utility.

The findings from this investigation complement the thermal manikin results presented earlier. And these results directly inform design refinements to enhance the garment's cooling efficiency, ergonomic properties, and user acceptance—ultimately advancing our goal of developing effective thermal protection for workers in hot environments.

## **8.2 Methods**

### **8.2.1 Participants**

The study recruited twelve healthy male college students who volunteered to participate. Participants had a mean ( $\pm$  SD) age of  $26 \pm 1.9$  years, height of  $180.2 \pm 2.5$  cm, weight of  $71.7 \pm 4.1$  kg, BMI of  $22.1 \pm 1.2$  kg/m<sup>2</sup>, and body surface area of  $1.9 \pm 0.05$  m<sup>2</sup>. All participants received comprehensive information about the experimental procedures and potential risks before providing written informed consent. Exclusion criteria included any history of heat-related illness, cardiovascular, metabolic, or respiratory disease. Participants were instructed to refrain from consuming tea, coffee, and alcohol for at least 24 hours before each test session. The experimental protocol was approved by the Human Subjects Ethics Sub-Committee of the Hong Kong Polytechnic University (protocol number HSEARS20240702002).

### **8.2.2 Clothing**

The ventilation cooling garment (VCG) developed in Chapter 6, which was designed for occupational workers in hot environments, was used in this study. The system is designed as a vest with a bag to hold the cooling source and a cooling unit to provide cooling air. We tested the prototype through thermal manikin and the prototype 2 with the low speed setting which showed the best cooling performance was chosen in this study. During testing, participants wore a standard UV-protective shirt over the VCG to simulate outdoor working conditions. Beneath this ensemble, subjects wore basic undergarments including an undervest, short pants, underwear, and socks. All garments were preconditioned in a climatic chamber for 24 hours prior to the human trials.

### **8.2.3. Protocol**

The experiment was conducted in a climatic chamber maintained at 35°C with 50% relative humidity and 0.1 m/s air velocity to simulate summer outdoor conditions. Participants completed two 120-minute trials: one using cooling garment and one without cooling garment (control). Each session began with a 30-minute acclimatization period, during which participants received briefings on test procedures and perceptual rating scales. After changing into the provided clothing and being fitted with monitoring devices, participants walked on a treadmill at 4.5 km/hour for 60 minutes[214], followed by a 30-minute recovery period before removing equipment and exiting the chamber. For safety, tests were immediately stopped if core temperature exceeded 38°C, heart rate surpassed 95% of average maximum, or participants

requested termination due to fatigue. In such cases, participants would repeat the test during their next visit. Importantly, participants retained the right to stop the test at any time for any reason.

## 8.2.4. Measurements

### 8.2.4.1 Physiological measurement

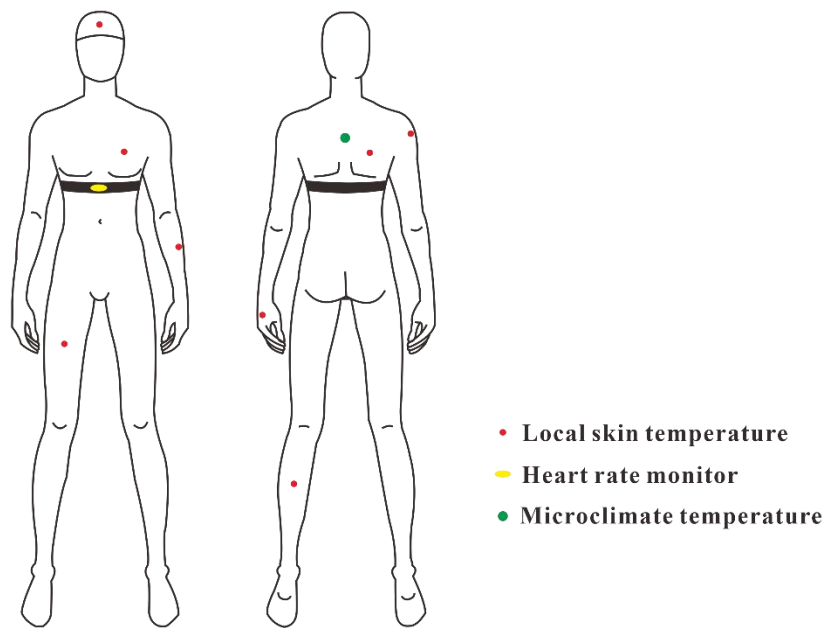
Core body temperature was measured at 5-minute intervals using an Ear Thermometer (ThermoScan 7 IRT6520, BRAUN). The microclimate temperature inside the UV shirt was monitored every minute via digital thermometers (DS1923, iButton) attached to the upper back area. Heart rate was measured every minute through heart rate monitor (H10, Polar). Skin temperature was recorded continuously at one-minute intervals throughout the test using sensors (DS1923, iButton) secured with waterproof adhesive tape (PVC, 3M) at eight locations: forehead, left upper chest, right scapula, left arm, right arm, left hand, left calf, and right anterior thigh. Mean skin temperature was calculated using the eight-point weighting method specified in the ISO 9886 standard (Table 8.1).

**Table 8. 1** Measuring sites and weighting coefficients.

Measuring sites	Forehead	Right scapula	Left Upper chest	Right arm	Left arm	Left hand	Right anterior	Left calf
Weighting coefficients	0.07	0.175	0.175	0.07	0.07	0.05	0.19	0.2

The mean skin temperature, is obtained from the following formula:

$$t_{sk} = \sum k_i t_{ski}$$



**Figure 8. 1** Measuring sites of heart rate, skin temperature, and microclimate temperature.



**Figure 8. 2** A subject wearing the VCG walking on a treadmill.

#### **8.2.4.2 Subjective evaluation**

Subjective thermal assessments were collected at the beginning of each trial and at 10-

minute intervals throughout. Eight parameters were evaluated: whole and upper body thermal sensation, whole and upper body wetness sensation, whole and upper body thermal comfort, thermal satisfaction, and thermal preference, with mean values calculated for each.

Participants rated whole-body and upper-body thermal sensation on a nine-point scale from -4 (very cold) to +4 (very hot), with 0 representing neutral. Wetness sensation for both whole body and upper body was rated on a seven-point scale from -3 (very wet) to +3 (very dry), with 0 indicating neutral. Thermal comfort was assessed on a five-point scale ranging from -4 (extremely uncomfortable) to 0 (comfortable). Thermal satisfaction utilized a five-point scale from -4 (extremely unsatisfied) to 0 (satisfied). Finally, thermal preference was rated on a seven-point scale from -3 (much cooler) to +3 (much warmer).

**Table 8. 2** Subjective measurement scales

Scales	Thermal sensation	Wetness sensation	Thermal comfort sensation	Thermal satisfaction	Thermal preference
-4	Very cold		Extremely uncomfortable	Extremely unsatisfied	
-3	Cold	Very wet	Very uncomfortable	Very unsatisfied	Much cooler
-2	Cool	Wet	Uncomfortable	Unsatisfied	Cooler
-1	Slightly cool	Slightly wet	Slightly uncomfortable	Slightly unsatisfied	A little cooler
0	Neutral	Neutral	Comfortable	Satisfied	No change
1	Slightly warm	Slight dry			A little warmer
2	Warm	Dry			Warmer

3	Hot	Very dry			Much warmer
4	Very hot				

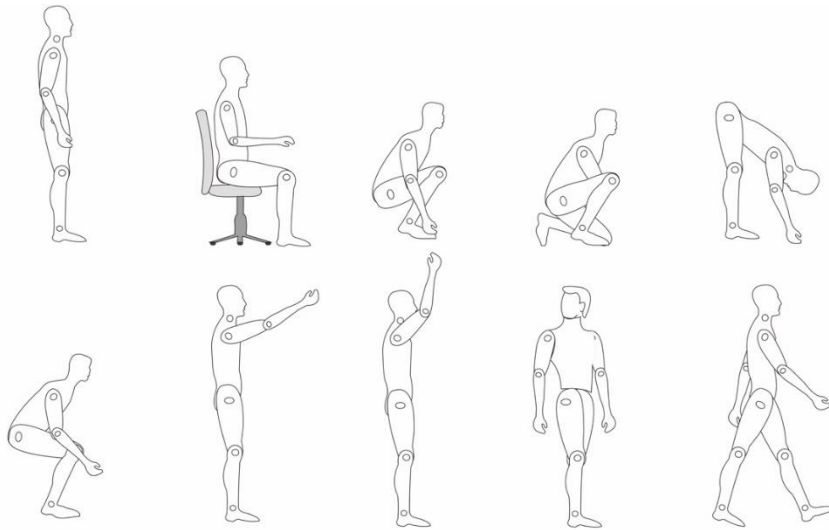
### 8.2.4.3 Wearing trial

Following the experiments, participants completed evaluations covering aesthetics, wearing comfort, and body movement comfort. The aesthetic assessment addressed design, material, color, handfeel, and appearance, using a seven-point Likert scale from -3 (very unsatisfied) to +3 (very satisfied). Wearing comfort evaluation examined ease of wearing, ease of removal, fit, flexibility, and safety, also rated on a seven-point Likert scale from -3 (very unsatisfied) to +3 (very satisfied). These assessments were conducted in the same climatic chamber. For the body movement comfort evaluation, participants rated their comfort on a seven-point scale from -3 (very uncomfortable) to +3 (very comfortable) after they performed ten distinct postures: standing, sitting, squatting, one-legged kneeling, back-bending, knee-bending, arm-raising, overhead work with one or both arms, twisting, and walking (Fig. 4.4).

**Table 8. 3** Wearing trial scales

Scales	Aesthetic	Wearing comfort	Body movement comfort
-3	Very unsatisfied	Very unsatisfied	Very uncomfortable
-2	Unsatisfied	Unsatisfied	Uncomfortable

-1	Slightly unsatisfied	Slightly unsatisfied	Slightly uncomfortable
0	Neutral	Neutral	Comfortable
1	Slightly satisfied	Slightly satisfied	Slightly comfortable
2	Satisfied	Satisfied	Comfortable
3	Very satisfied	Very satisfied	Very comfortable



**Figure 8. 3** Ten different postures for body movement comfort evaluation.

### **8.2.5. Statistical analysis**

Data analysis was conducted using IBM SPSS Statistics (Version 19.0, IBM Corporation). Results are reported as mean  $\pm$  standard deviation unless otherwise indicated. Paired t-tests compared physiological and perceptual outcomes both temporally and between cooling and non-cooling treatments. All statistical analyses used a 95% confidence level.

## **8.3. Results and discussion**

### **8.3.1 Physiological parameters**

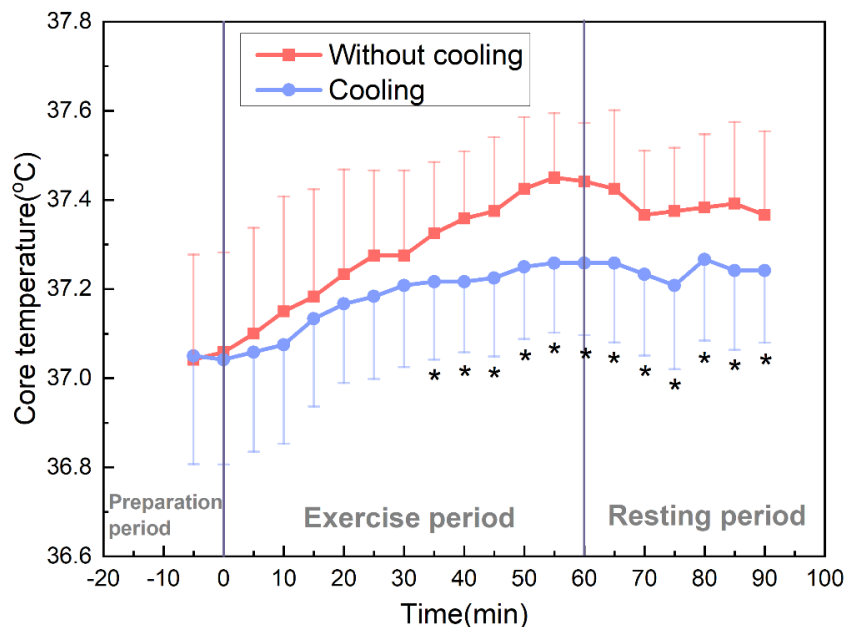
#### **Core temperature**

Figure 8.4 illustrates the core temperature responses during a protocol consisting of preparation, exercise, and resting periods, comparing conditions with and without cooling intervention from the VCG. The initial preparation period (-5 to 0 minutes) represents the transition phase where participants, having completed a 30-minute stabilization period, donned the experimental garments and moved to the treadmill. For the cooling condition, this included activating the cooling system. During this period, participants were being prepared for the exercise phase.

The exercise period (0 to 60 minutes) was defined as beginning precisely when the treadmill reached the target speed of 4.5 km/h. As participants entered the exercise period (0 to 60 minutes), core temperatures in both conditions demonstrated an increase. Without cooling, core temperatures rose more rapidly, reaching a peak of approximately 37.45°C around the 50-minute. In contrast, with cooling intervention, the core temperature increase was more moderated, peaking at only about 37.25°C. A significant difference ( $p < 0.05$ ) in core temperature between the control and cooling conditions was observed from the 35th minute onwards, with a maximum difference of approximately 0.2°C between the two conditions.

During the resting period (60 to 90 minutes), participants in the non-cooling condition maintained elevated core temperatures around 37.4°C with minimal reduction. Conversely, those with cooling support maintained lower core temperatures consistently around 37.25°C.

The sustained 0.2°C difference in core temperature between conditions demonstrates the VCG's practical physiological impact. The core temperature reduction is meaningful, which represents an alleviation of thermal strain during physical exertion. These findings shown that the VCG effectively mitigates core temperature elevation during standardized exercise and facilitates improved thermal recovery, which could have important implications for physical performance, comfort, and heat-related illness prevention in thermally challenging environments.



\*: P<0.05

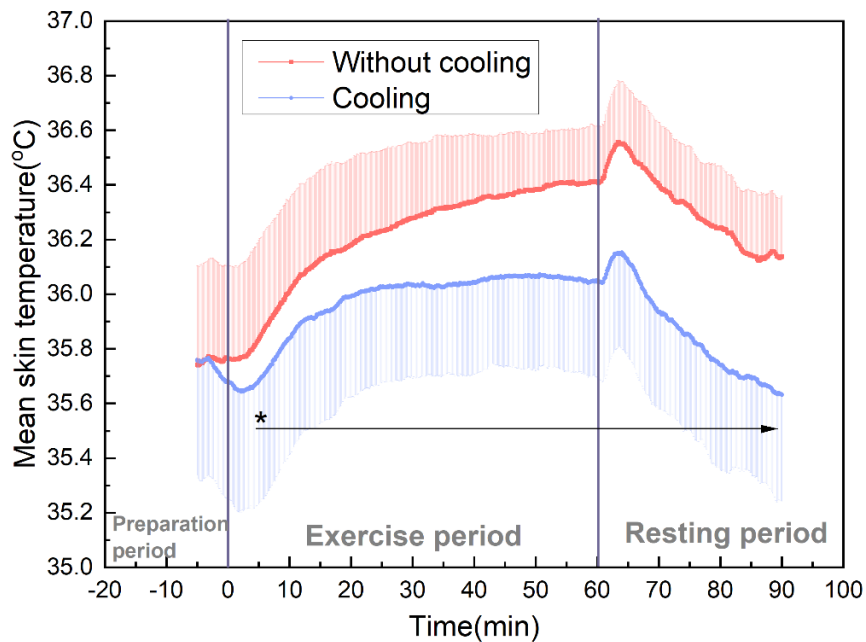
**Figure 8. 4** Core temperature during preparation, exercise and resting periods with and without cooling.

### **Mean skin temperature**

Figure 8.5 illustrates the mean skin temperature responses comparing conditions with and without cooling intervention from the VCG. During the exercise period (0 to 60 minutes), mean skin temperature rose steadily to approximately 36.4°C by the end of the exercise period without cooling. In contrast, with cooling intervention, the skin temperature increase was relatively lower, stabilizing around 36.0°C. A significant difference ( $p < 0.05$ ) in mean skin temperature between the control and cooling conditions was observed throughout the exercise period, with an average difference of approximately 0.4°C between the two conditions.

During the resting period (60 to 90 minutes), both conditions showed an initial sharp increase in skin temperature, likely due to the sudden stop of the treadmill from 4.5 km/h to 0 km/h. After this brief increase, participants in the non-cooling condition showed a gradual decrease in skin temperature to about 36.1°C by the end of the recording period. Those with cooling support experienced a more notable decrease, reaching approximately 35.6°C by the end of the protocol.

The consistent 0.4°C difference in mean skin temperature between conditions demonstrates the direct effect of the VCG on the skin's thermal state. This difference in skin temperature is physiologically relevant as it indicates effective heat extraction from the body surface.



\*:  $P < 0.05$

**Figure 8. 5** Mean skin temperature during preparation, exercise and resting periods with and without cooling.

### Local skin temperature

To better examine how skin surface temperatures varied across specific body regions, the local skin temperature measurements were analyzed for comparison. The left upper chest temperature data (Fig. 8.6(a)) shows that both conditions started at similar values around 35.8°C during the preparation period. During the exercise period, the non-cooling condition showed a moderate increase to approximately 36.2°C, while the cooling condition maintained relatively stable temperatures around 35.9-36.0°C. A significant difference was observed from the 50<sup>th</sup> of exercise period to the end of resting period.

After exercise ended, both conditions showed a brief sharp increase in temperature,

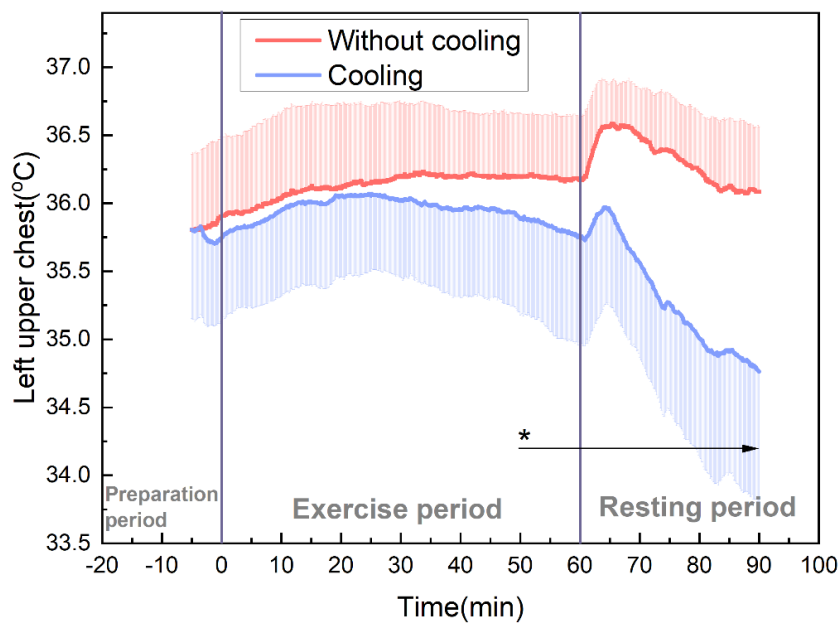
likely due to the sudden stop of the treadmill. Following this increase, the cooling condition showed a much steeper decrease in temperature, falling to approximately 34.7°C by the end of the recording period. In contrast, the non-cooling condition decreased more gradually to about 36.1°C. The temperature difference between conditions was greatest during the resting period, reaching approximately 1.4°C by the end of the testing period.

Compared with the skin temperature of the left upper chest site, the right scapula temperature (Fig. 8.6(b)) showed more immediate and pronounced differences between conditions. Starting from similar values of about 36.1°C during preparation, the non-cooling condition showed a steady increase reaching approximately 36.9°C by the end of exercise, while the cooling condition decreased rapidly to about 35.5°C and then remained stable.

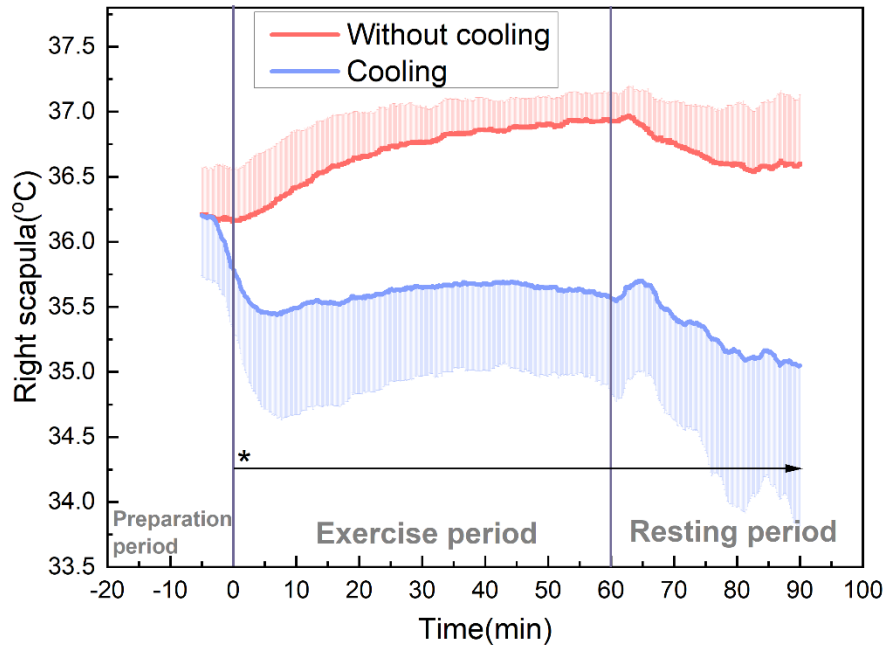
Statistical significance ( $p < 0.05$ ) was observed from the beginning of the exercise period through the end of the resting period. During the resting period, the right scapula temperature in cooling condition continued to decrease, reaching approximately 35.0°C by the end, while the non-cooling condition decreased to about 36.5°C, maintaining a temperature difference of approximately 1.5°C between conditions.

These results demonstrate that the cooling garment had different effects depending on body location. This difference was caused by the cooling air distribution which resulted from the design of the cooling garment. The right scapula showed an immediate and

sustained cooling effect throughout the entire protocol, while the left upper chest showed a delayed significant cooling effect that was most pronounced during the recovery period. Overall, the cooling intervention effectively reduced local skin temperatures in both regions, with the effect being more immediate and pronounced in the scapular region.



(a)



(b)

\*:  $P < 0.05$

**Figure 8. 6** Local skin temperature (Left upper chest(a) and Right scapula temperature(b)) during preparation, exercise and resting periods with and without cooling.

### Heart rate

Figure 8.7 shows heart rate responses during the three experimental phases (preparation, exercise, and resting) comparing cooling and non-cooling conditions. During the preparation period (-5 to 0 minutes), heart rates were similar between conditions, starting at approximately 85 bpm and showing some minor fluctuations as participants prepared for exercise. When participants start the exercise, heart rates in both conditions increased rapidly to approximately 105 bpm. Throughout the exercise period (0 to 60 minutes), both conditions showed a gradual increase in heart rate, but with clear differences between them. The non-cooling condition showed a steeper increase,

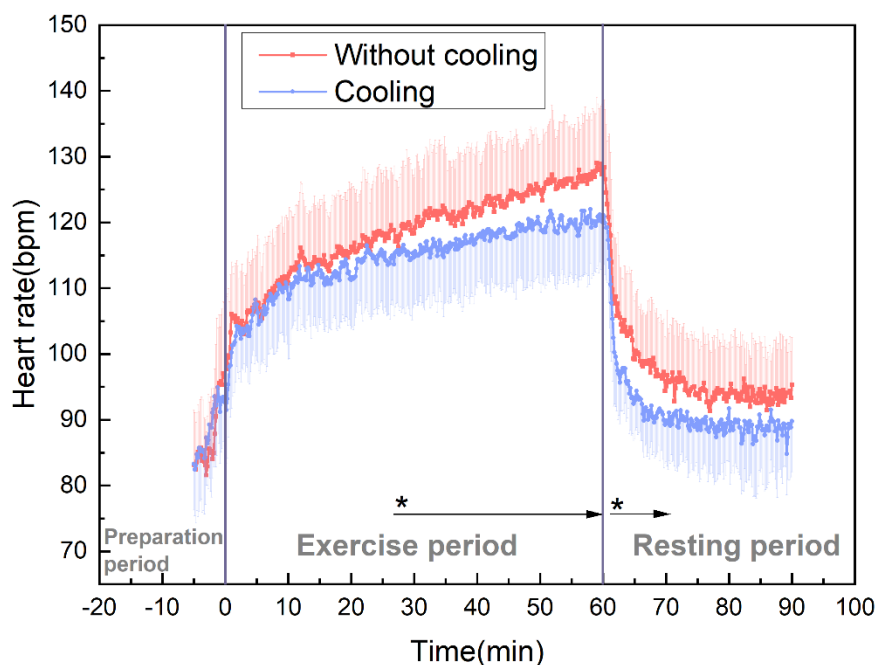
reaching approximately 128 bpm by the end of exercise. In contrast, the cooling condition showed a more moderate increase, reaching approximately 120 bpm. This difference between conditions was statistically significant ( $p < 0.05$ ) from the 25th of the exercise period.

The average difference in heart rate between conditions during exercise was approximately 8 bpm, suggesting reduced cardiovascular strain with cooling. The widening gap between conditions as exercise progressed indicates that the cooling benefit became more pronounced with continued exercise duration.

When exercise stopped at the 60-minute, heart rates in both conditions decreased sharply. During the resting period (60 to 90 minutes), heart rates continued to decrease but stabilized at different levels - approximately 95 bpm for the non-cooling condition and 90 bpm for the cooling condition. This difference remained statistically significant ( $p < 0.05$ ) for the first 10 minutes of the recovery period. We did not analyze the significance for the last 20 minutes of the recovery period because the post-exercise interview was conducted during this time, and it is known that talking affects heart rate measurements.

These results demonstrate that the cooling intervention effectively reduced cardiovascular strain both during moderate-intensity exercise and during recovery. The lower heart rates in the cooling condition suggest that the body was able to maintain

thermal balance with less cardiovascular effort, which could potentially improve exercise tolerance and reduce fatigue during physical activity in hot environments.



\*:  $P < 0.05$

**Figure 8. 7** Heart rate during preparation, exercise and resting periods with and without cooling.

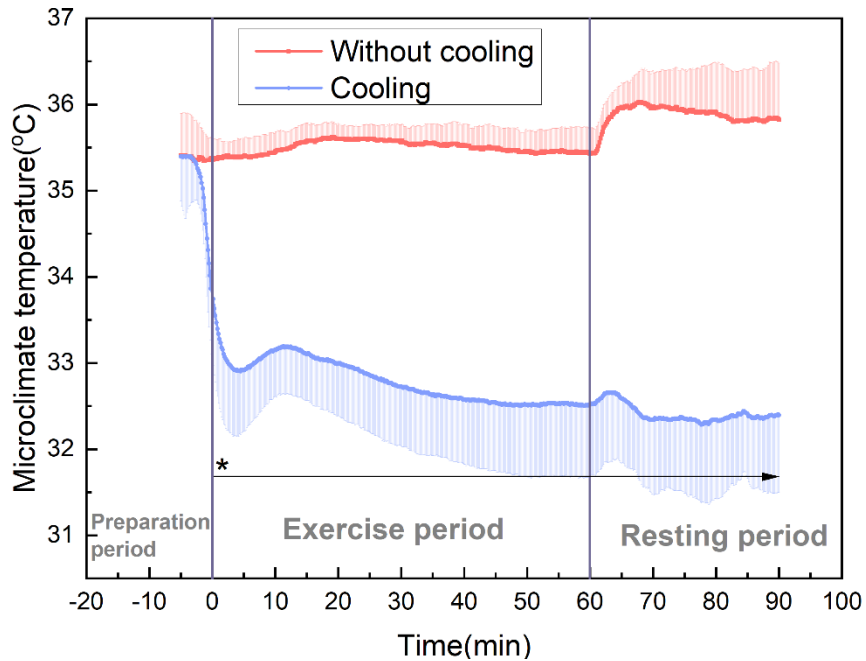
### 8.3.2 Microclimate temperature

The cooling condition showed an immediate and obvious decrease in microclimate temperature, dropping rapidly from about 35.5°C to approximately 33.0°C within the first 5 minutes. The microclimate temperature in the cooling condition continued to decrease gradually throughout the exercise period, reaching approximately 32.5°C by the 60-minute. In contrast, the non-cooling condition maintained a relatively stable microclimate temperature throughout the exercise period, which was about 35.5°C. The difference between conditions was obvious (approximately 3°C) and statistically

significant ( $p < 0.05$ ) throughout the entire exercise period.

When exercise stopped at the 60-minute, both conditions showed a brief temperature fluctuation. The non-cooling condition exhibited a small increase to approximately 36.0°C, while the cooling condition showed a small rise followed by continued decline. The increase may be attributed to the sitting position, which potentially affected airflow directed toward the temperature sensor. During the resting period (60 to 90 minutes), the microclimate temperature in the non-cooling condition stabilized around 35.9°C, while the cooling condition-maintained temperatures around 32.3-32.4°C. The significant difference ( $p < 0.05$ ) between conditions persisted throughout the resting period.

Figure 8.8 provides clear evidence of the cooling garment's effectiveness in reducing the microclimate temperature by approximately 3°C throughout both exercise and recovery periods. This significant microclimate temperature reduction explains the enhanced heat transfer from the skin to the environment, thereby facilitating better thermoregulation during exercise. The consistent and significant cooling effect also explains the observed differences in skin temperatures and heart rates seen in previous results, demonstrating the possibility for the improved thermal comfort and reduced cardiovascular strain with the cooling intervention



\*:  $P < 0.05$

**Figure 8. 8** Microclimate temperature during preparation, exercise and resting periods with and without cooling.

### 8.3.3 Subjective assessments

#### Thermal sensation

Figure 8.9 present subjective thermal sensation ratings for whole body (a) and upper body (b) throughout the 90-minute experimental protocol, comparing conditions with and without the cooling intervention. For whole body thermal sensation, both conditions began with slightly warm ratings at the start of exercise, with values of approximately 0.7 for the cooling condition and 1.0 for the non-cooling condition. As exercise progressed, participants' thermal sensations in the non-cooling condition rising from "slightly warm" (~1.0) to "warm-to-hot" (~2.8) by the 60-minute. In contrast, participants using the cooling garment experienced a more gradual increase in thermal

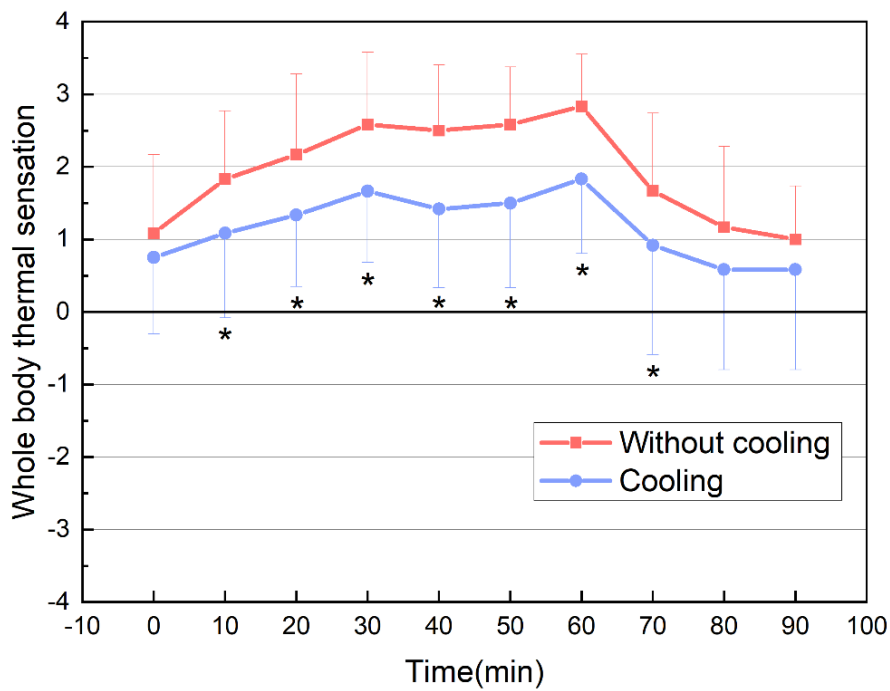
discomfort, with ratings only reaching "slightly warm-to-warm" (~1.8) at the same timepoint. Statistical analysis revealed significant differences ( $p < 0.05$ ) between conditions after 10 minutes' exercise till the end of exercise period, indicating consistently improved thermal comfort with cooling throughout the period.

During the recovery phase, thermal sensation decreased in both conditions, with the non-cooling group showing a reduction from approximately 2.8 to 1.0 (slightly warm), while the cooling group approached neutral thermal sensation with final values around 0.6. A significant difference remained at the 70-minute of recovery, suggesting prolonged benefits of the cooling intervention even after exercise.

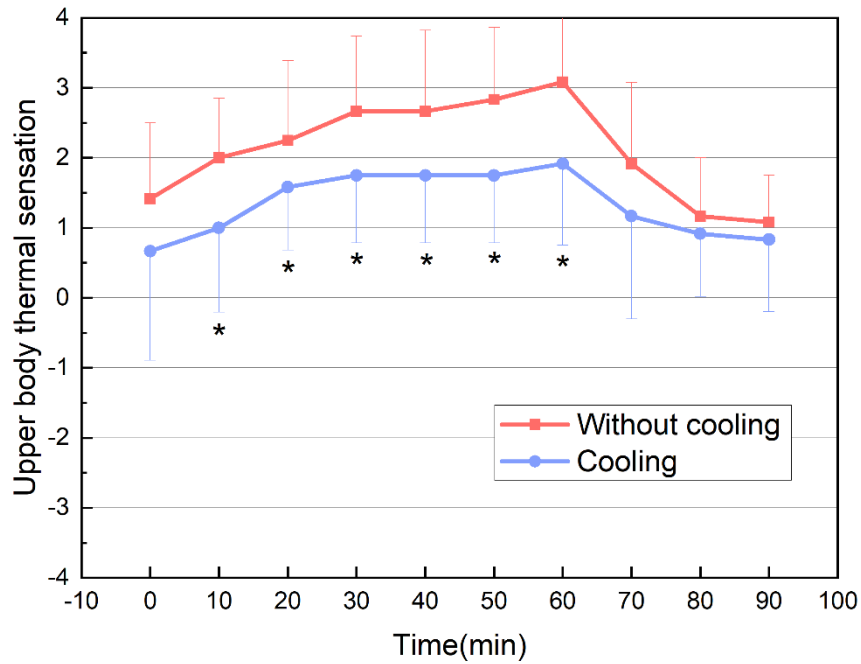
The upper body thermal sensation data revealed similar changes but with more pronounced effects. Initial sensations were warmer than whole-body ratings, starting at approximately 0.7 for the cooling condition and 1.4 for the non-cooling condition. Without cooling, upper body thermal sensation increased to approximately 3.0 (hot) by the end of exercise, whereas with cooling, the sensation remained lower at around 2.0 (warm). The cooling intervention produced significant improvements in upper body thermal comfort at all measured timepoints during exercise (from 10 to 60 minutes), demonstrating consistent effectiveness throughout the protocol.

The more pronounced and consistent cooling effect observed in the upper body assessment aligns with the design of the cooling garment, which was specifically

developed for the upper body region. Both figures demonstrate that thermal discomfort increased with exercise duration, but the cooling intervention effectively mitigated this increase by approximately one full point on the thermal sensation scale. These subjective data provide evidence that the cooling garment effectively improved thermal sensation particularly for upper body sensation during both exercise and recovery phases



(a)



(b)

\*:  $P < 0.05$

**Figure 8.9** Changes in the (a) whole body and (b) upper body thermal sensations during exercise and resting periods with and without cooling.

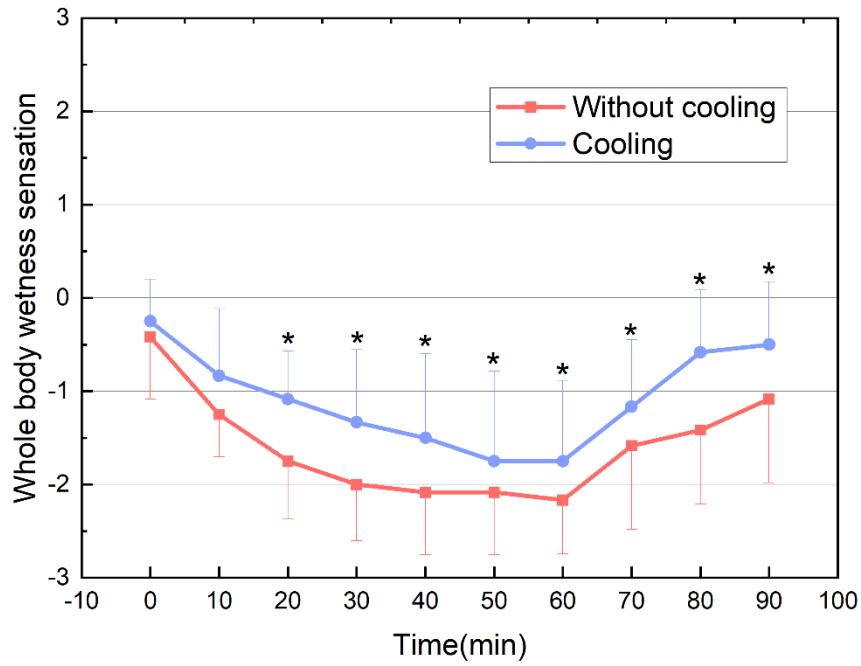
### Wetness sensation

Figure 8.10 present subjective wetness sensation ratings for the whole body (a) and upper body (b) throughout the 90-minute experimental protocol comparing conditions with and without cooling intervention. As exercise started, the whole body wetness sensation increased in both conditions, with the non-cooling condition showing a more rapid increase, approaching -2.0 ("wet") between 40-60 minutes of exercise. The cooling condition demonstrated a more moderate increase in wetness sensation, reaching approximately -1.7 at its peak. Statistical analysis revealed significant differences ( $p < 0.05$ ) between conditions from 20th to 90th minutes. During recovery, wetness sensation gradually decreased in both conditions as sweat evaporated, though

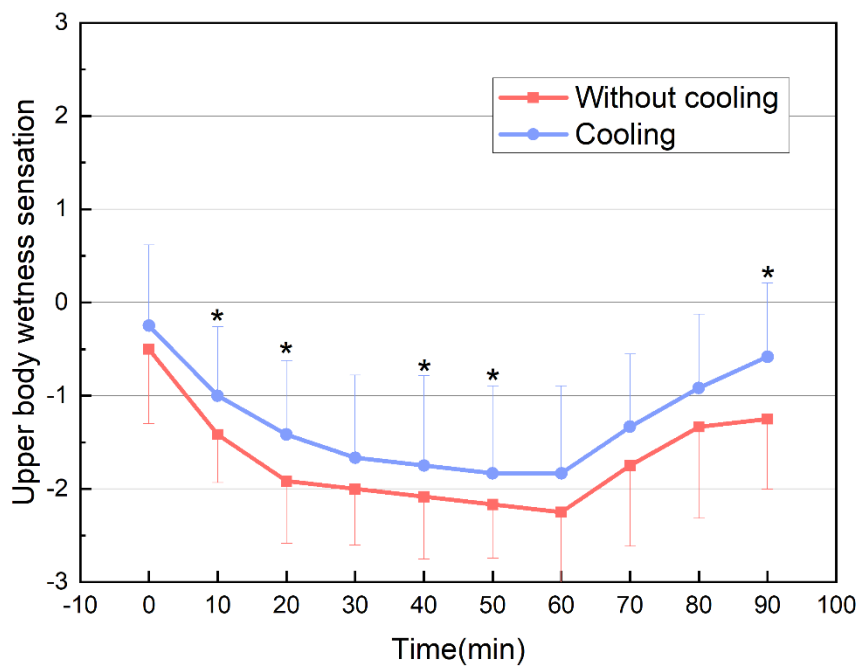
the cooling condition consistently maintained lower wetness sensation values compared to the non-cooling condition.

The upper body wetness sensation showed similar trend but with some distinct characteristics. Both conditions showed increased wetness sensations during activity. The non-cooling condition reached more pronounced wetness sensations in the upper body, approaching -2.3 ("wet" to "very wet") at the 60-minute timepoint, while the cooling condition maintained less extreme wetness sensations, reaching only about -1.8 at its peak. Significant differences between conditions were only observed at 10th, 20th, 40th, and 50th minutes and 90th minutes (during late recovery). The recovery phase showed decreasing wetness sensations in both conditions, with the cooling condition consistently reporting less wetness than the non-cooling condition.

Interestingly, the whole body wetness sensation showed a bigger difference between cooling and non-cooling conditions compared to upper body wetness, despite the cooling garment being specifically designed for the upper body. This suggests that the localized cooling intervention had broader effects on overall wetness perception, possibly by influencing whole-body thermal comfort and sweat dynamics. For both measurements, the non-cooling condition consistently produced more extreme wetness sensations throughout the exercise period, indicating that participants felt significantly drier when using the cooling garment despite engaging in the same physical activity.



(a)



(b)

\*: P<0.05

**Figure 8. 10** Changes in the (a) whole body and (b) upper body wetness sensations during exercise and resting periods with and without cooling.

**Thermal comfort sensation**

Figure 8.11 present subjective thermal comfort ratings for the whole body (a) and upper body (b) throughout the 90-minute experimental protocol comparing conditions with and without cooling intervention. As exercise progressed, the whole body thermal discomfort increased in both conditions. In the non-cooling condition, whole body thermal discomfort increased steadily, reaching its maximum at approximately -2.0 at the 60-minute. In contrast, the cooling condition demonstrated significantly better thermal comfort throughout exercise, with discomfort levels stabilizing at approximately -1 to -1.3 during the exercise period. Statistical analysis revealed significant differences ( $p < 0.05$ ) between conditions from 30th to 80th minutes.

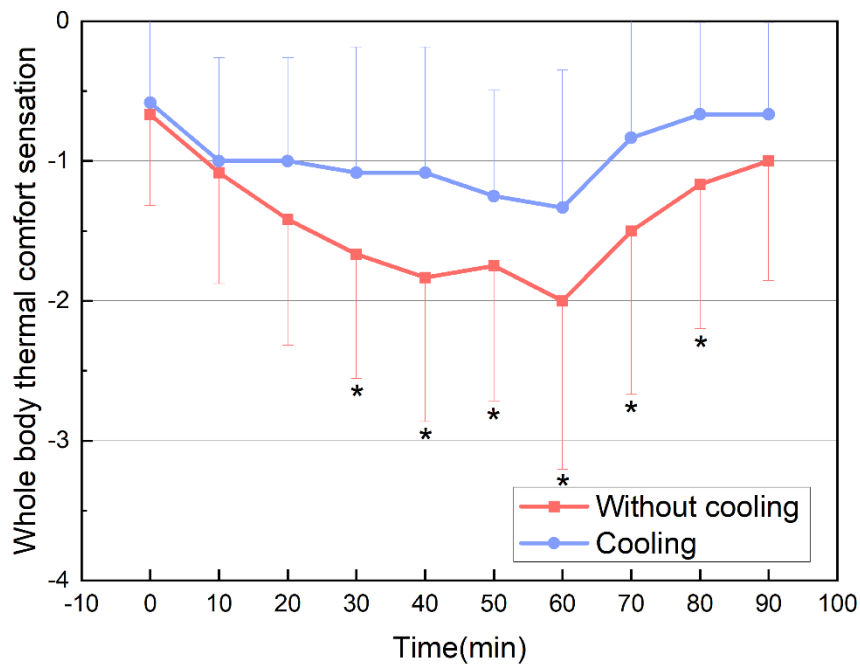
During the recovery phase (60-90 minutes), thermal comfort improved in both conditions, with the cooling condition approaching values of -0.7 by the end of recovery while the non-cooling condition reached approximately -1.0. This suggests a more complete recovery of thermal comfort when the cooling intervention was employed.

For the upper body thermal comfort sensation, the non-cooling condition showed worse thermal comfort in the upper body, reaching approximately -2.2 at its peak at 60 minutes. The cooling condition maintained substantially better thermal comfort throughout exercise, with discomfort levels generally staying between -1.0 and -1.4. Significant differences between conditions were observed from 20th to 80 minutes.

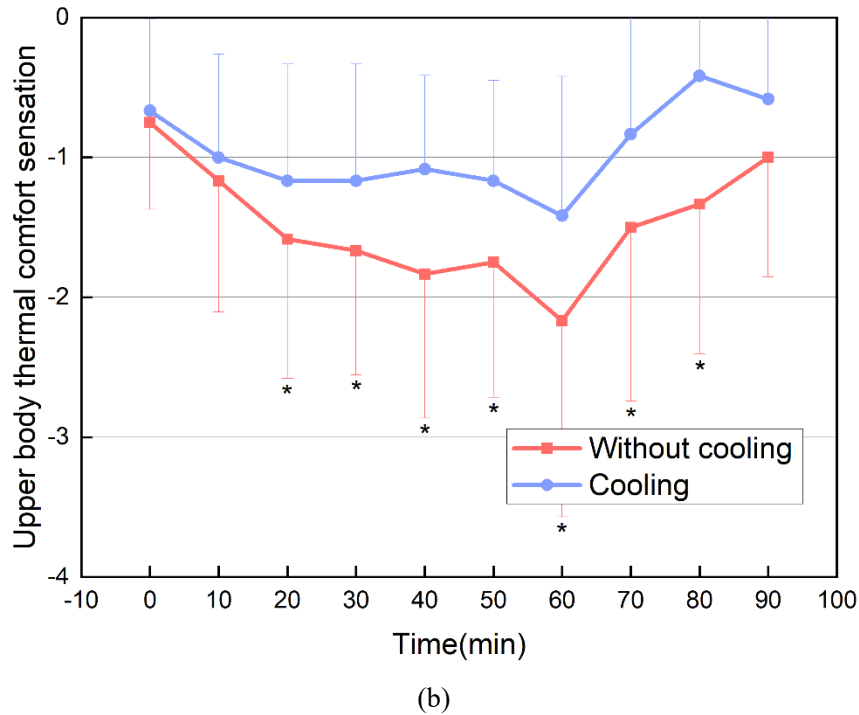
During recovery, both conditions showed improving thermal comfort, with the cooling

condition experiencing a better improvement, reaching approximately -0.4 at the 80-minute mark before settling at about -0.6 by the end of the protocol. The non-cooling condition recovered to approximately -1.0 by the end of the recovery phase.

The thermal comfort data for both whole body and upper body demonstrate consistent benefits of the cooling intervention. The difference between conditions was particularly pronounced during the latter phases of exercise (40-60 minutes), suggesting that the cooling garment's effectiveness may become more critical as thermal strain accumulates during prolonged exercise. These findings demonstrate that the cooling garment effectively improved subjective thermal comfort during exercise and recovery phases.



(a)



\*:  $P < 0.05$

**Figure 8. 11** Changes in the (a) whole body and (b) upper body thermal comfort sensations during exercise and resting periods with and without cooling.

### Thermal satisfaction and thermal preference

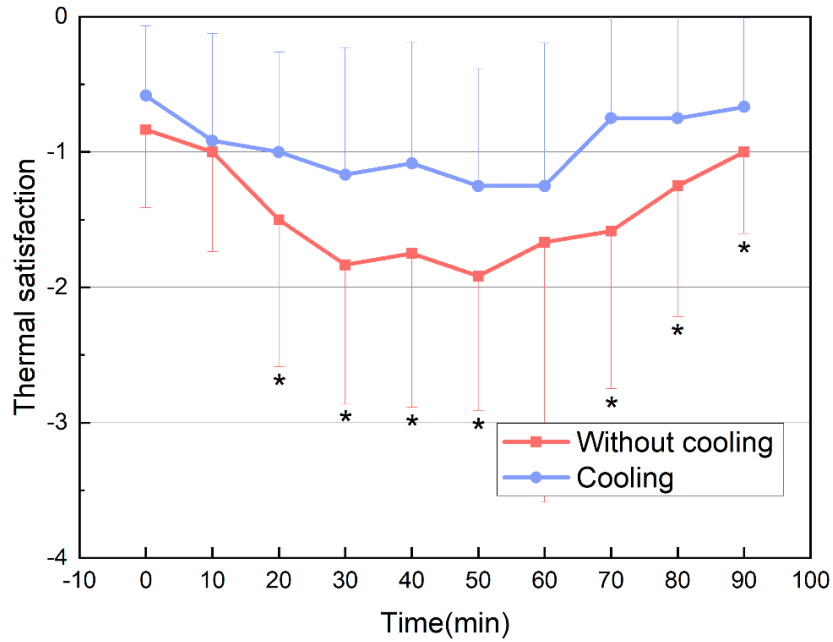
The thermal satisfaction scale ranges from 0 (satisfied) to -4 (Extremely unsatisfied), with increasingly negative values representing greater dissatisfaction (see Fig 8.12a). After exercise started, thermal dissatisfaction increased in both conditions. In the non-cooling condition, thermal dissatisfaction increased steadily, reaching its maximum at approximately -1.9 at the 50-minute mark. In contrast, the cooling condition demonstrated significantly better thermal satisfaction throughout the exercise period, with dissatisfaction levels fluctuating between -1.0 and -1.3 during the exercise period. Statistical analysis revealed significant differences ( $p < 0.05$ ) between conditions from 20th to 90th minutes. During the recovery phase (60-90 minutes), thermal satisfaction

improved in both conditions, with the cooling condition approaching values of -0.7 by the end of recovery while the non-cooling condition reached approximately -1.0. This indicates a more complete recovery of thermal satisfaction when the cooling intervention was employed.

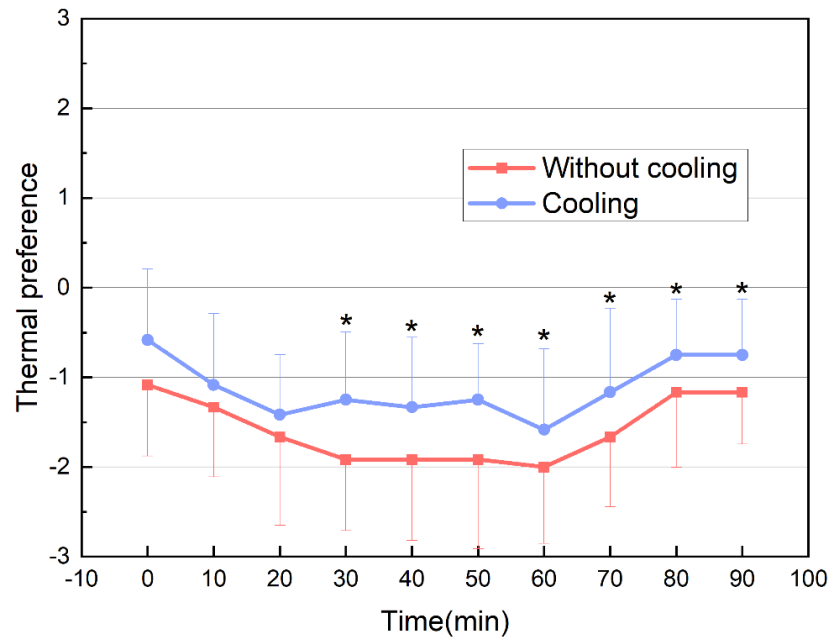
Following twenty minutes of heat exposure, participants in both groups desired cooler temperatures, with the cooling condition showing a modest preference rating of -0.6 compared to the stronger preference of -1.1 in the non-cooling condition (see Fig 8.12b). As exercise continued, the desire for cooler conditions intensified in the non-cooling condition, reaching approximately -2.0 during the 30-60 minute period. The cooling condition maintained less extreme thermal preference values throughout exercise, generally between -1.2 and -1.5, suggesting that participants felt closer to their ideal thermal state when using the cooling garment. Significant differences between conditions were observed from 30th to 90th minutes. During recovery, thermal preference in both conditions moved closer to neutral, with the cooling condition showing a more substantial shift toward neutral preference.

These findings demonstrate that the cooling garment effectively improved both thermal satisfaction and thermal preference during exercise and recovery phases. The cooling intervention successfully prevented the deterioration of thermal satisfaction that typically occurs during exercise in hot conditions and kept participants closer to their preferred thermal state. These results provide comprehensive evidence that the cooling

intervention delivered meaningful improvements in multiple dimensions of subjective thermal experience.



(a)



(b)

\*: P<0.05

**Figure 8. 12** Changes in the (a) Thermal satisfaction (b) Thermal preference during exercise and resting periods with and without cooling.

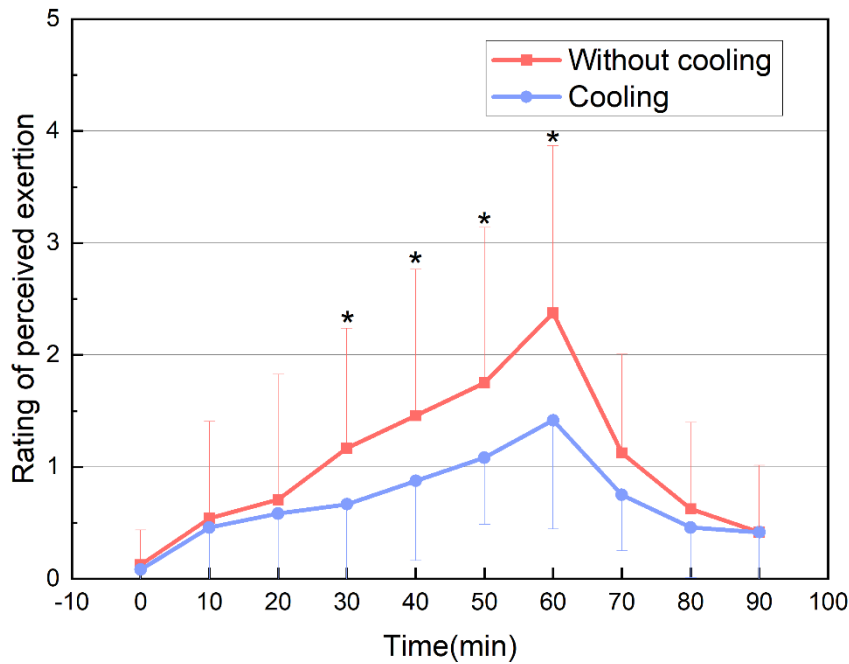
### **Rating of perceived exertion**

At the beginning of the experiment, both conditions showed minimal perceived exertion (approximately 0.1), indicating participants were at rest before exercise began. As the protocol progressed, the RPE increased gradually in both conditions. In the non-cooling condition, the RPE rose more rapidly, reaching values of approximately 1.1 at 30 minutes, 1.5 at 40 minutes, 1.7 at 50 minutes, and peaking at 2.3 at the 60-minute point. This indicates an increase in total fatigue throughout the exercise part of the protocol. In contrast, the cooling condition demonstrated a more modest increase in the RPE, with values of approximately 0.6 at 30 minutes, 0.9 at 40 minutes, 1.1 at 50 minutes, and peaking at 1.4 at the 60-minute point. This represents approximately 40-50% lower RPE compared to the non-cooling condition during the same time periods. Statistical analysis revealed significant differences ( $p < 0.05$ ) between conditions from 30th to 60th minutes during exercise period, suggesting that the cooling intervention's effect on the RPE becomes more pronounced as exercise duration increases.

During the recovery phase, the RPE decreased rapidly in both conditions, returning to near-baseline levels by the 90-minute point. The cooling condition maintained lower perceived exertion values during early recovery (70 minutes), although the difference between conditions diminished as recovery progressed.

These findings demonstrate that the cooling intervention effectively reduced subjective ratings of perceived exertion during exercise. This reduction in perceived exertion

suggests that cooling allowed participants to experience the same exercise intensity as requiring less effort, which could have important implications for exercise tolerance. Lower perceived exertion may allow individuals to exercise longer or at higher intensities before reaching limiting levels of discomfort or fatigue.



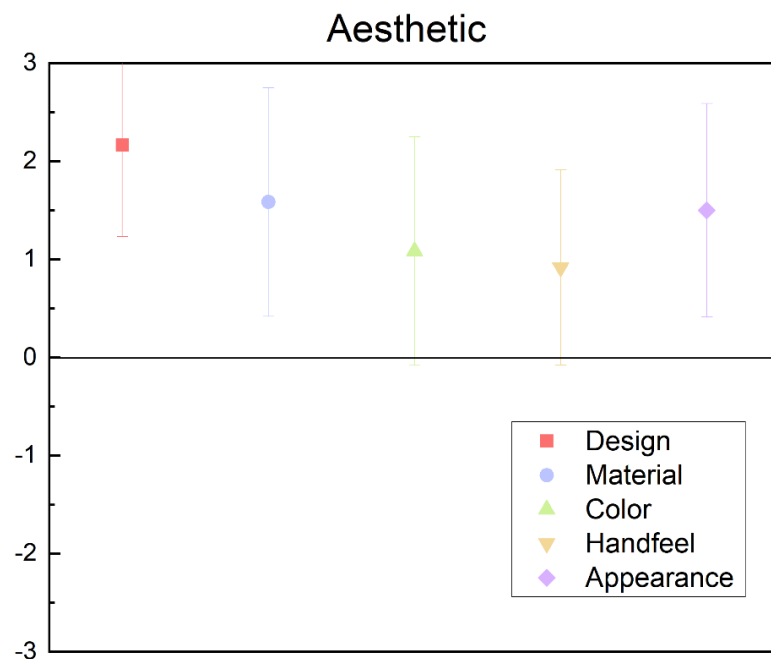
\*:  $P < 0.05$

**Figure 8. 13** Rating of perceived exertion during exercise and resting periods with and without cooling.

### 8.3.4 Wearing trial results

Figure 8.14 presents aesthetic evaluations across five attributes of a cooling garment, measured on a scale from -3 to +3. All attributes received positive ratings, indicating generally favorable aesthetic perceptions, with Design receiving the highest mean score (approximately 2.1), followed by Material and Appearance (both around 1.5-1.6), then Color (approximately 1.1), and finally Handfeel with the lowest though still positive rating (approximately 0.9). Notable in this data is the substantial variability across

participants as indicated by the error bars, particularly pronounced for Material, Appearance, and Design attributes. This variability suggests considerable diversity in individual aesthetic preferences or experiences. These findings suggest that while the item being evaluated demonstrates strong aesthetic qualities particularly in its design concept and material selection, the tactile experience might represent an area for potential improvement.



**Figure 8. 14** Aesthetic evaluation for subjects wearing VCG.

Figure 8.15 presents an evaluation of wearing comfort across five attributes of a wearable cooling garment. All attributes received relatively positive ratings, suggesting generally favorable perceptions of the product's wearability. The "Fit" attribute emerged as the most highly rated aspect (approximately 1.8), indicating that participants found the item's sizing and fitting to body shape particularly satisfactory, which can be attributed to the adjustable design of the vest. "Flexibility" received the second highest rating (approximately 1.2), followed by "Easy to wear" and "Easy to remove" (both

around 0.9-1.0), with "Safety" receiving the lowest though still positive rating (approximately 0.8). The lower safety ratings might reflect limited awareness among participants about safety considerations in outdoor work environments. The variability suggests considerable diversity in user experiences or expectations regarding these comfort attributes. The overall pattern indicates that while the item performs well in terms of fit and flexibility, there may be opportunities to improve aspects related to safety and ease of donning and doffing.

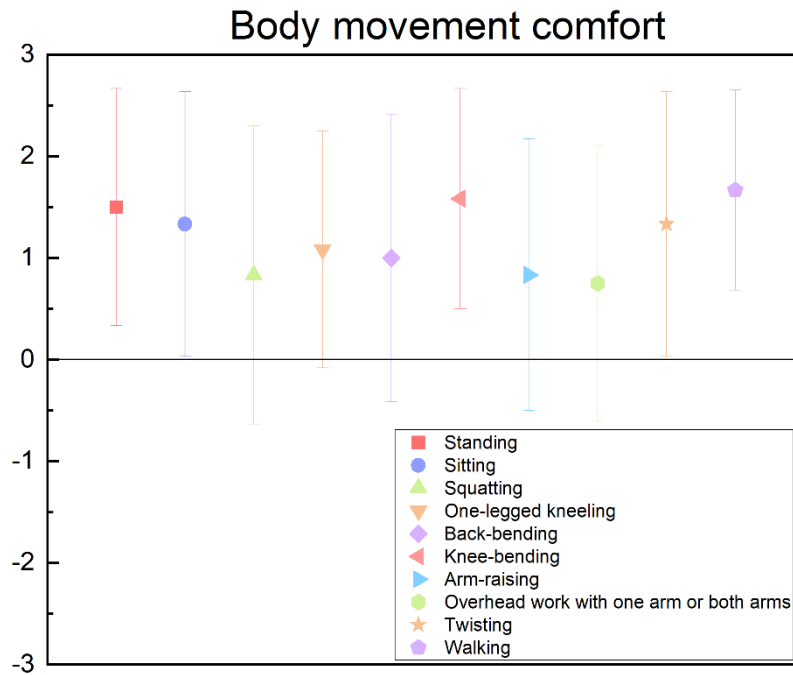


**Figure 8. 15** Wearing comfort evaluation for subjects wearing VCG.

Figure 8.16 presents an evaluation of body movement comfort across ten different postures or movements while wearing what appears to be a functional garment. All assessed movements received positive comfort ratings on a scale from -3 to +3, indicating that the garment provides acceptable comfort across various body positions and activities. Walking emerged as the highest-rated movement (approximately 1.7), closely followed by Standing (approximately 1.5) and Twisting (approximately 1.3).

Moderate comfort ratings were observed for Sitting, One-legged kneeling, Knee-bending, and Back-bending (all ranging between approximately 1.0-1.6). The movements associated with the lowest comfort scores, though still positive, were Squatting, Arm-raising, and Overhead work (all between approximately 0.8-0.9). The weight of the cooling garment in the lower back area may affect the subjective assessment of the postures related to back bending and arm raising. The variability shown in the error bars reflects differences in how individuals experienced comfort during these movements while wearing the garment. This variability could reflect differences in body morphology, movement patterns, personal preferences, or specific interactions between the garment design and individual anatomy.

The results suggest that the garment performs best during whole-body movements like walking and standing, and relatively well during torso movements like twisting, but may present more challenges during movements requiring significant joint flexion, particularly at the shoulders, hips, and knees. These findings provide valuable guidance for design refinements, indicating that improvements might focus on enhancing comfort during squatting, arm-raising, and overhead work.



**Figure 8. 16** Body movement comfort evaluation for subjects wearing VCG.

## 8.4. Discussion

The present study systematically evaluated the efficacy of a newly designed ventilation cooling garment (VCG) in mitigating thermal strain and enhancing wearer comfort during physical activity under hot environmental conditions. The results show significant physiological benefits and subjective improvements provided by the cooling intervention, with implications for occupational applications in thermally challenging environments.

The observed moderation of core temperature elevation, which maintained a mean difference of approximately 0.2°C compared to the control condition, align with previous findings on active garment-based cooling systems [85] [209]. This finding is physiologically meaningful as even small reductions in core temperature can

significantly decrease the risk of heat-related illnesses and improve safety in high-heat settings [215]. The consistent reduction in mean skin temperature, averaging 0.4°C, further supports the garment's capacity to enhance whole-body heat dissipation. Regional analysis revealed the most pronounced local cooling at the scapular area (up to 1.5°C), reflecting the targeted airflow distribution incorporated into the VCG's design [38]. In contrast, the relatively limited cooling in the chest region confirmed a microclimate cooling effect [85] and suggests an opportunity for further optimization of airflow pathways to achieve more uniform thermal relief.

The VCG's impact on cardiovascular strain, as evidenced by an average reduction of 8 bpm in heart rate during exercise, is particularly noteworthy. Lower heart rates under thermal stress are indicative of reduced cardiovascular load and improved thermal tolerance, both of which are critical for sustained performance and health [216]. Collectively, these physiological outcomes validate the effectiveness of the VCG in attenuating heat strain during moderate-intensity activity.

Microclimate temperature measurements confirmed the garment's direct cooling action, with a consistent 3°C reduction compared to the non-cooling condition, explaining the enhanced heat transfer from the body. Although the microclimate is not so low as we expected, it's microclimate modification still translated into meaningful improvements across all subjective thermal assessments [217]. This microclimate cooling is likely the primary mechanism underlying the improvements observed in subjective thermal

sensation, comfort, and satisfaction ratings. Participants reported significantly better thermal sensation, wetness sensation, thermal comfort, thermal satisfaction, and thermal preference when using the cooling garment. This finding highlights the unique contribution of air-circulation technology in personal cooling. The reduction in perceived exertion (40-50% lower during exercise) was particularly notable, suggesting improved exercise tolerance that could have practical implications for work performance in hot conditions.

The wearing trial results indicated generally positive responses to the garment's aesthetics, with design aspects receiving the highest ratings. Wearing comfort assessments revealed satisfactory fit and flexibility, though safety features could be improved. Body movement evaluations demonstrated that the garment performed well during whole-body movements like walking and standing, with some limitations during movements requiring significant joint flexion.

These findings demonstrate that the newly designed VCG provides effective physiological cooling that translates into meaningful improvements in thermal comfort and reduced exertion during physical activity in hot environments. The garment successfully combines functional cooling with acceptable wearability characteristics. Future development could focus on optimizing the cooling distribution, enhancing safety features, and improving comfort during complex body movements. This research establishes the VCG as a promising intervention for mitigating heat stress during

occupational or recreational activities in thermally challenging environments.

It is important to recognize certain limitations of this laboratory study: Our design of the cooling garment was based on previous research [210, 211] that recommended the upper back area as the best cooling part. However, during our post-experiment interviews, 83% of participants expressed a preference for additional cooling in the chest area. Additionally, 41% of participants indicated a desire for supplementary head cooling, suggesting that future studies should also consider this region when designing personal cooling garments. It is important to note that our study did not specifically evaluate local thermal comfort at targeted body sites; our focus was limited to movement comfort across different postures. To address this gap, future research should incorporate assessments of local thermal comfort, potentially through detailed questionnaires, and explore alternative local cooling designs. Moreover, as posture can influence the effectiveness of cooling, further work is needed to systematically investigate how different postures impact cooling performance.

## **8.5. Conclusion**

In summary, this study demonstrates that the VCG is an effective and promising intervention for reducing physiological heat strain and enhancing subjective comfort during physical activity in hot environments. The integration of targeted cooling and ergonomic design features offers significant potential for applications in occupational

health, particularly for individuals exposed to high thermal loads. Continued research and iterative development are recommended to further refine the garment's performance and broaden its applicability.

## **Chapter 9 Conclusions and Suggestions for Future Research**

### **9.1 Conclusions**

This thesis presents a comprehensive investigation of personal cooling garments (PCGs), from theoretical foundations to practical applications, with a focus on developing and evaluating novel cooling solutions for healthcare workers and individuals in hot environments.

The literature review established a thorough classification of PCGs based on their cooling mechanisms: air cooling, evaporative cooling, phase-change cooling, liquid cooling, thermoelectric cooling, and radiative cooling. Each type presents distinct advantages and limitations that determine their suitability for specific applications. The review also examined the diverse applications of PCGs across various occupational contexts and outlined methodologies for evaluating their performance through thermal manikin testing, human trials, and thermoregulation modeling.

For healthcare workers in hospital environments, the thesis developed a Wearable Cooling and Dehumidifying System (WCDS) designed to address the specific challenges of heat stress when wearing personal protective equipment. Through thermal manikin testing, the WCDS demonstrated superior cooling capacity compared to commercially available alternatives, maintaining a stable cooling power of approximately 60 Watts over a 4-hour testing period. This represents a cooling power

per unit weight 2.9 to 3.9 times higher than other tested cooling garments. While liquid cooling garments (LCG) and phase change cooling garments (PCCG) provided good initial cooling, their performance declined significantly over time, highlighting the WCDS's advantage in stability and sustained cooling effect. Subject testing of the WCDS confirmed these findings, showing significant reductions in core temperature and meaningful improvements in thermal sensation and reduced wetness perception. Importantly, the WCDS achieved these benefits without imposing additional cardiovascular strain or compromising mobility. Microclimate measurements demonstrated the system's ability to effectively reduce both temperature and humidity within the protective clothing, addressing two critical factors in thermal discomfort.

For individuals working in hot environments, the thesis developed and evaluated a Ventilation Cooling Garment (VCG). Thermal manikin testing revealed that the VCG provided superior cooling power compared to commercial air cooling garments, particularly at lower airflow rates while minimizing energy consumption and noise. Human subject testing demonstrated the VCG's effectiveness in moderating physiological responses to heat stress, maintaining core temperatures approximately 0.2°C lower and reducing heart rates by approximately 8 bpm during exercise compared to non-cooling conditions. Subjective assessments showed significant improvements in thermal comfort, with a 40-50% reduction in perceived exertion during physical activity. Both developed cooling systems effectively addressed the limitations of existing commercial options while considering the specific requirements of their intended

applications. The WCDS overcame the challenges of moisture management and cooling sustainability in enclosed protective clothing, while the CACG provided effective cooling with optimized airflow distribution in hot environments without causing skin wetness discomfort.

This research demonstrates that properly designed personal cooling garments can significantly mitigate heat stress and improve both physiological responses and subjective thermal comfort in challenging thermal environments. The methodological approach combining systematic design processes, thermal manikin testing, and human subject evaluation provides a comprehensive framework for developing and assessing personal cooling technologies for specific occupational settings.

## **9.2 Suggestions**

However, there are still limitations and opportunities for future research in the field of personal cooling garments. Some suggestions for future research include:

1. **Optimization of cooling efficiency:** Future research should focus on refining the cooling distribution to target physiologically critical regions while minimizing energy consumption. For the WCDS, investigating alternative thermoelectric configurations or cooling flow patterns could enhance efficiency. For the VCG, optimizing the ergonomic design based on quantitative field study data, particularly focusing on ventilation

pathway optimization to enhance cooling effectiveness during sustained physical activity in high-temperature environments..

2. Extended field testing and long-term evaluation: While laboratory studies provide controlled assessment, extended field testing in actual occupational settings would provide valuable insights into real-world performance, durability, and user acceptance over prolonged periods. For healthcare applications, evaluating the WCDS during authentic clinical tasks could identify additional design considerations specific to medical environments. For the VCG, field testing across diverse environmental conditions with varying temperature, humidity, and solar radiation would enhance understanding of its performance boundaries.

3. Material innovations and sustainability: Research into advanced materials with enhanced thermal properties, moisture management capabilities, and antimicrobial characteristics could improve both performance and practical aspects of cooling garments. For the WCDS, incorporating antimicrobial textiles and surface treatments would address infection control requirements critical in healthcare settings. And For the VCG, development should focus on recyclable components, directly addressing growing sustainability concerns in wearable technology development..

4. Standardization and comparative evaluation methodologies: Developing standardized testing protocols specifically designed for personal cooling garments

would facilitate meaningful comparisons between different technologies and designs. This could lead to industry standards and certification processes that help users select appropriate cooling solutions for specific applications.

5. Expansion to other applications: While this thesis focuses on healthcare workers and outdoor workers, future research can explore the potential applications of personal cooling garments in other fields, such as sports, military, and aerospace. Each application may have unique requirements and challenges that need to be addressed through tailored cooling solutions.

By addressing these research gaps and opportunities, future studies can contribute to the continuous improvement and widespread adoption of personal cooling garments, ultimately promoting occupational health, safety, and well-being in various settings

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