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Assessment of Wearable Cooling and Dehumidifying System Used under Personal Protective Clothing through Human Subject Testing

Yiying Zhou [1], Lun Lou [2] and Jintu Fan [1,3,4,*]

[1] School of Fashion and Textiles, The Hong Kong Polytechnic University, Hong Kong; 21052594r@connect.polyu.hk
[2] Energy Sector, Nano and Advanced Materials Institute, Hong Kong Science Park, Hong Kong
[3] Research Center of Textiles for Future Fashion, The Hong Kong Polytechnic University, Hong Kong
[4] Research Institute of Sports Science and Technology, The Hong Kong Polytechnic University, Hong Kong
* Correspondence: jin-tu.fan@polyu.edu.hk

Abstract: Healthcare professionals wearing personal protective equipment (PPE) during outbreaks often experience heat strain and discomfort, which can negatively impact their work performance and well-being. This study aimed to evaluate the physiological and psychological effects of a newly designed wearable cooling and dehumidifying system (WCDS) on healthcare workers wearing PPE via a 60 min treadmill walking test. Core temperature, mean skin temperature, heart rate, and subjective assessments of thermal sensation, wetness sensation, and thermal comfort were measured throughout the test. Additionally, ratings of wearing comfort and movement comfort were recorded during a wearing trial. The results showed that the WCDS significantly reduced core temperature, improved thermal sensation, and reduced wetness sensation compared to the non-cooling condition. The microclimatic temperature within the PPE was significantly lower in the cooling condition, indicating the WCDS's ability to reduce heat buildup. The wearing trial results demonstrated general satisfaction with the wearability and comfort of the WCDS across various postures. These findings contribute to the development of enhanced PPE designs and the improvement in working conditions for healthcare professionals on the frontlines during outbreaks.

Keywords: personal protective equipment; healthcare workers; wearable cooling and dehumidifying system; thermal comfort; wearing comfort

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1. Introduction

Healthcare professionals frequently work in environments with a high risk of viral transmission. Personal protective equipment (PPE) is an essential component of isolation precautions designed to protect these individuals from potential exposure to infectious agents [1,2]. However, the prolonged use of PPE can lead to additional physical and mental stress, such as heat strain, fatigue, and a potential decrease in work performance [3–6]. A study revealed that healthcare professionals experienced heat strain symptoms approximately 25 times more frequently when working with PPE compared to working without it [7].

To alleviate 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 [8–10], liquid cooling garments [11–14], and ventilation cooling systems [15,16], all of which demonstrated significant improvements in thermal comfort. However, PCM/ice vests and liquid cooling garments have limitations in operating time [17,18], and both of these cooling methods can cause skin wetness, which affects skin wetness comfort [19]. 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 phase-change cooling vests, liquid cooling garments, and air-cooling systems, Lou et al. [20] developed a novel and lightweight wearable cooling and dehumidifying system (WCDS) for use in hazardous environments to reduce skin wetness and improve thermal comfort.

When examining the effects of personal cooling garments on healthcare professionals, it is crucial to differentiate between thermal sensation and thermal comfort. Thermal sensation refers to an individual's immediate perception of coldness or warmth, which is subjective and can vary among individuals. In contrast, thermal comfort is a state of mind that indicates contentment with the surrounding thermal environment, taking into account both physiological and psychological aspects. Although thermal sensation is an essential aspect of thermal comfort, it is not the only determining factor. For example, a healthcare worker may experience a neutral thermal sensation while wearing PPE but still feel uncomfortable due to skin wetness caused by sweating. Consequently, when assessing the effectiveness of personal cooling garments, it is necessary to consider both thermal sensation and thermal comfort.

Previous studies have not considered the specific challenges posed by the use of PPE during a pneumonia outbreak. Furthermore, the precise psychological and physiological effects of wearing WCDS under personal cooling garments in real working conditions have not been adequately investigated. To address this gap, additional research is necessary to gain a comprehensive understanding of the psychological and physiological impact of WCDS in the working environment, which will facilitate optimal design and improved performance. Therefore, this study was conducted to evaluate the physiological and psychological impact of a newly designed cooling suit on healthcare workers. The study analyzed the impact of WCDS on the thermal comfort of healthcare workers by monitoring skin temperature, core temperature, and heart rate. Additionally, a subjective evaluation questionnaire and a wearing trial, which included assessments of wearing comfort and movement comfort, were administered. The aim was to obtain a comprehensive assessment of the effectiveness of the WCDS application by examining the thermal perception, physiological responses, and wearing comfort of healthcare workers. This research provides valuable insights for the design of future PPE and contributes to enhancing the occupational environment for those on the healthcare frontlines.

2. Methods

2.1. Participants

Eight healthy male college students voluntarily participated in the study. The participants had a mean age of 27 ± 2.1 years, height of 178.3 ± 2.2 cm, weight of 69.6 ± 3.6 kg, BMI of 21.8 ± 1.3 kg/m^2, and body surface area of 1.8 ± 0.1 m^2. Before participation, each participant was comprehensively informed about the experimental procedure and potential risks and provided 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 h prior to each test. The Human Subjects Ethics Sub-Committee of the Hong Kong Polytechnic University approved the experimental procedures under protocol number [HSEARS20210514003].

2.2. Clothing

The wearable cooling and dehumidifying system (WCDS) (Figure 1), developed by Lou et al. [20], is intended 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 (Tyvek 600 Plus, Dupont, Wilmington, DE, USA) 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 [21]. 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 h.

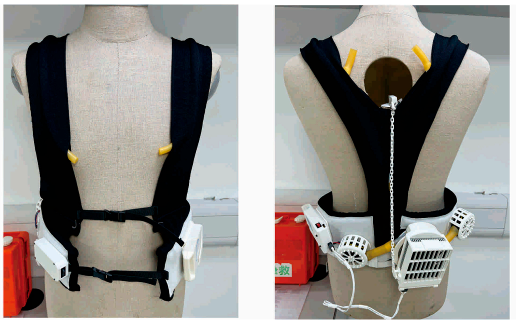


Figure 1. Wearable cooling and dehumidifying system (WCDS).

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 min experimental trials: one with a cooling garment (cooling) and a control trial (without cooling). Initially, subjects were given a 30 min 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 min, the participants walked on a treadmill at a speed of 3.0 km/h, representing a typical work intensity level [22] (Figure 2). After a 30 min 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.

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

2.4. Measurements

2.4.1. Physiological Measurement

Core body temperature measurements were recorded at one-minute intervals using a wearable sensor device (CORE, greenTEG). The 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; see Figure 3) 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 1).

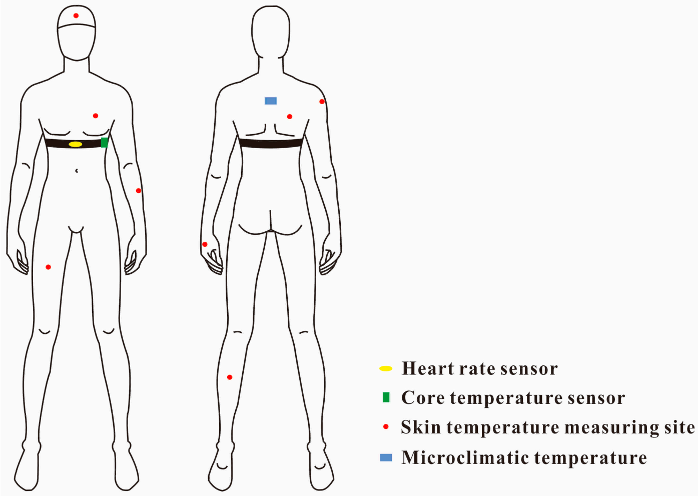


Figure 3. Measuring sites of heart rate, core temperature, skin temperature, and microclimatic temperature.

Table 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 via the following formula:

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

2.4.2. Subjective Evaluation

Thermal sensation, wetness sensation, and thermal comfort sensation were assessed initially and then every 10 min 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 (Figure 4a), 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 (Figure 4b), 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 (Figure 4c), ranging from −4 (extremely uncomfortable) to 0 (comfortable).

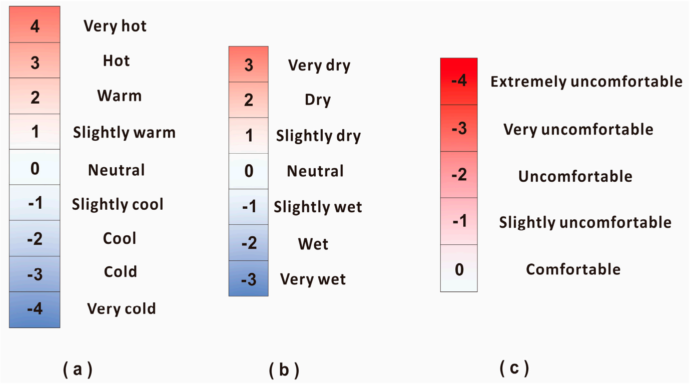


Figure 4. Subjective measurement scales: (**a**) thermal sensation; (**b**) wetness sensation; (**c**) thermal comfort.

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) (Figure 5a). 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 Figure 6). 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 5b).

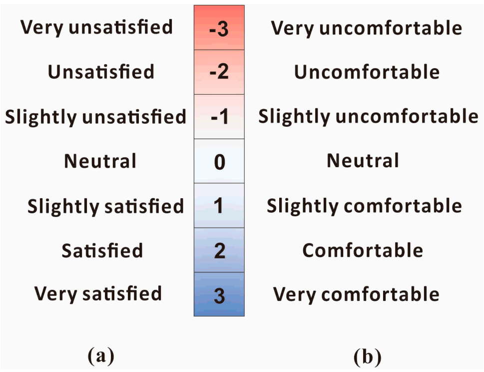


Figure 5. Wearing trial scales: (**a**) wearing comfort; (**b**) body movement comfort.

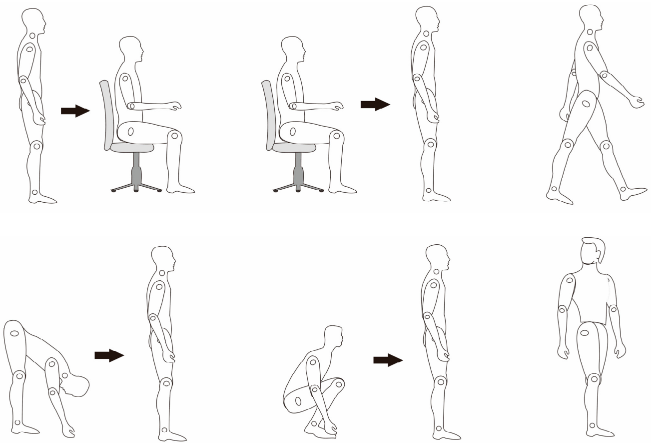


Figure 6. Six different postures for body movement comfort evaluation.

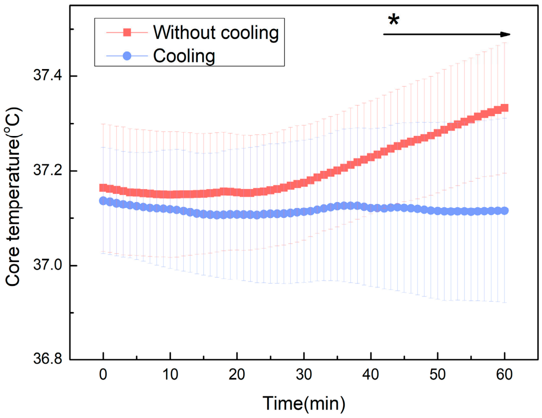
2.5. Statistical Analysis

Statistical data analysis was performed using IBM SPSS Statistics (Version 19.0, IBM Corporation). Unless otherwise specified, all values are presented as mean ± 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.

3. Results

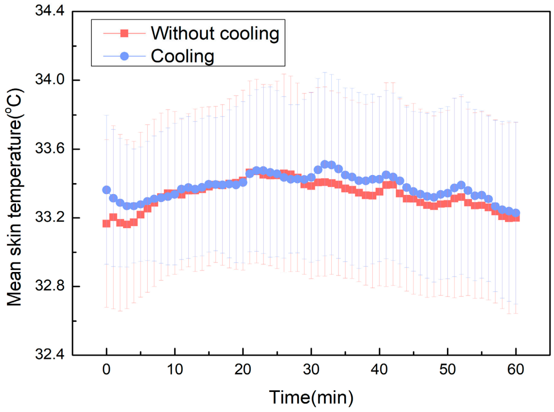
3.1. Physiological Parameters

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 (Figure 7a) was observed from the 42nd minute onwards, with a maximum difference of 0.22 °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 a 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 (Figure 7b). 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 subjects. It is known that the perspiration rate is closely related to the change in core temperature. The cooling effect of the WCDS resulted in less perspiration and lower skin wetness and 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 (Figure 7c).

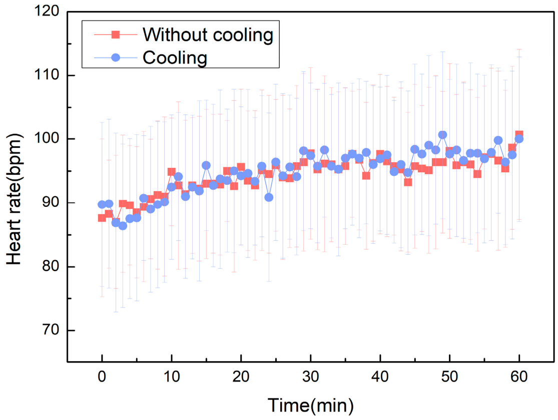


(**a**)

Figure 7. *Cont.*



(**b**)



(**c**)

Figure 7. Comparison of changes in the core temperature (**a**), mean skin temperature (**b**), and heart rate (**c**) between the control and cooling groups; *: $p < 0.05$.

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 personal protective clothing (Figure 8). The maximum temperature difference (5.3 °C) of the microclimate under the protective garment was recorded at the 28th minute of the experiment.

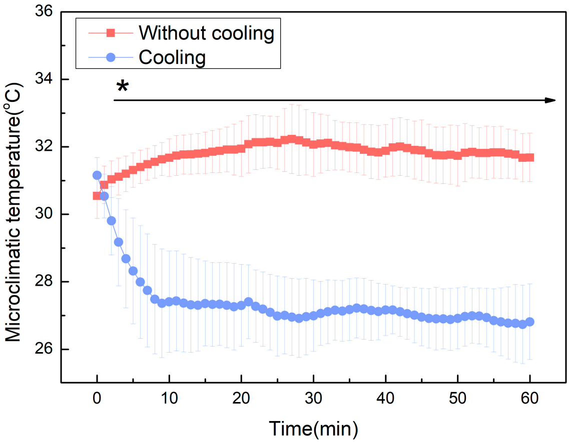
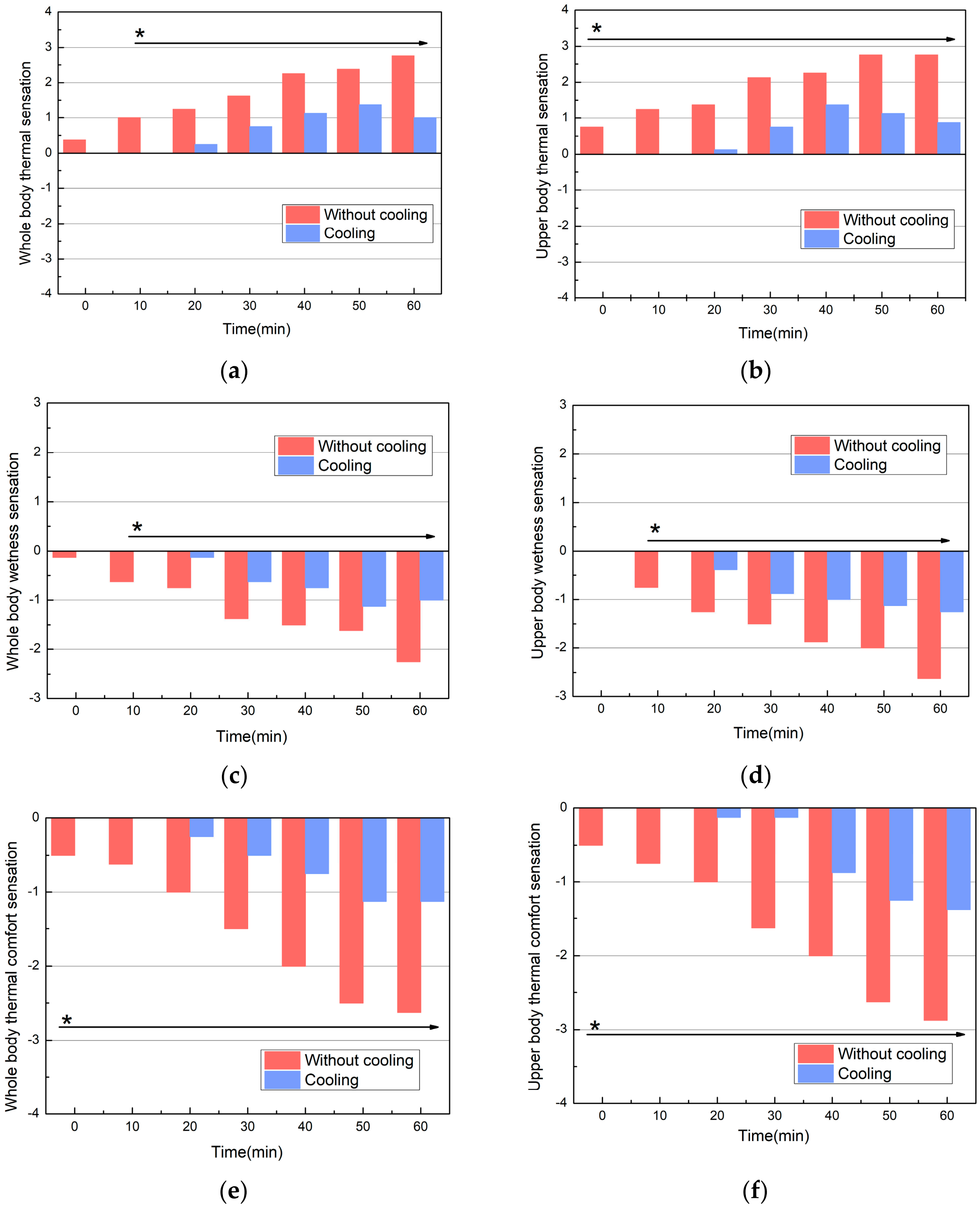


Figure 8. Changes in microclimatic temperature in the upper back area during the whole test period. *: $p < 0.05$.

3.3. Subjective Assessments

As depicted in Figure 9a,b, 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 the 10th minute 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.



(**a**) (**b**)

(**c**) (**d**)

(**e**) (**f**)

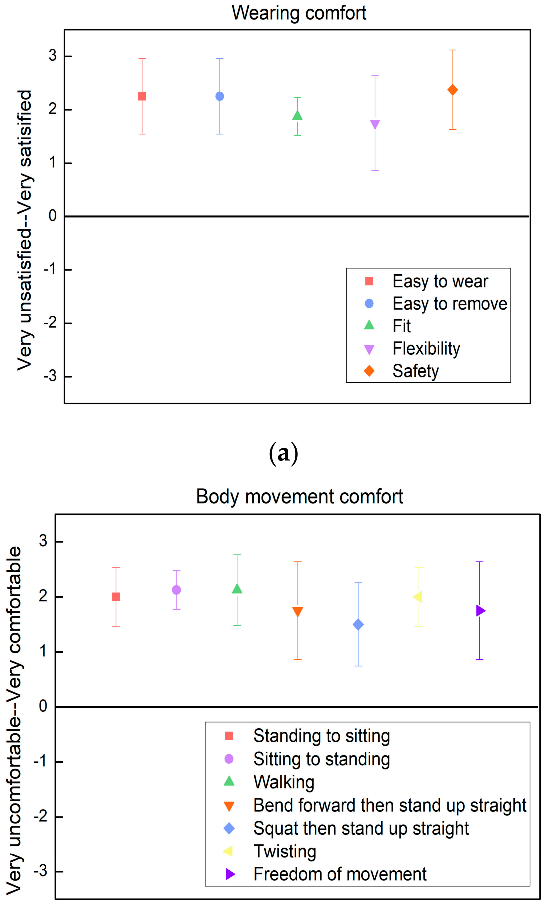
Figure 9. Time changes in the whole body-, upper body-thermal sensations (**a**,**b**), wetness sensation (**c**,**d**), and thermal comfort sensation (**e**,**f**) in the control and cooling groups. *: $p < 0.05$.

Figure 9c,d 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 the 10th minute, 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 the 10th minute, 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 subjects.

The whole-body thermal comfort sensation and upper-body thermal comfort sensation were presented in Figure 9e and 9f, 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.

3.4. Wearing Trial Results

The wearing comfort of WCDS is shown in Figure 10a. The data indicate a general satisfaction with wearability. Figure 10b 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 10. Wearing (**a**) and movement (**b**) comfort votes for subjects wearing WCDS.

4. Discussion

This study aimed to investigate the effectiveness of a wearable cooling and dehumidifying system (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 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 [23], indicating that the WCDS did not impose additional cardiovascular strain. Mean skin temperature was more likely to be affected by 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, the skin was covered by undergarments instead of being exposed to the cooling air, so the evaporative heat loss from the 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 [24]. Compared to a traditional air-cooling system, this system can effectively lower the microclimatic temperature and reduce the risk of infectious diseases caused by air cooling, which cools via air circulation from the surroundings. The significant reduction in microclimatic temperature 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. Conclusions

This study provides valuable insights into the effectiveness of a wearable cooling device system (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 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.

Author Contributions: Conceptualization, J.F., L.L. and Y.Z.; methodology, L.L. and Y.Z.; software, Y.Z.; validation, Y.Z.; formal analysis, Y.Z.; investigation, Y.Z.; resources, Y.Z.; data curation, Y.Z.; writing—original draft preparation, Y.Z.; writing—review and editing, J.F., L.L. and Y.Z.; visualization,

Y.Z.; supervision, J.F.; project administration, J.F.; funding acquisition, J.F. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data will be made available upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

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