

Article

New Design of Personal Protective Equipment for Handling Contagious Viruses: Evaluation of Comfort and Physiological Responses

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Abstract: The use of personal protective equipment (PPE) for virus handling has the side effect of heat stress, which requires intervention to improve. This study aimed to evaluate the comfort of a newly designed PPE ensemble for virus handling. Three types of PPE ensembles were tested: regular PPE as a control, PPE plus breathable cooling wear (cooling wear), and PPE plus a portable airflow cooling device (cooling device). Twelve participants simulated six activities, including physical activities, activities requiring concentration, and manual dexterity activities, for one hour. The microclimate conditions, perceived discomfort, and physiological responses were measured after each experimental activity. The results show that the use of cooling wear and a cooling device had a significant effect on the microclimate conditions, perceived comfort, and physiological responses of users, proving superior to the use of regular PPE. A cooling device can improve the microclimate more than cooling wear, thereby directly increasing perceived comfort and decreasing physiological responses. It can be concluded that the use of cooling wear and a cooling device effectively increases the comfort of wearing PPE. The cooling device is more suitable for use in tropical climates with hot and humid characteristics, so it is a better choice than cooling wear.

Keywords: discomfort; heat stress; intervention; physiological response; PPE for virus handling



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1. Introduction

Diseases caused by acute viral infections can cause severe epidemics or pandemics that affect millions of people over time. Past outbreaks include the H₁N₁ virus (Spanish flu) in 1918, the H₂N₂ influenza virus in 1957, the H₃N₂ influenza virus in 1968, the Hantaviruses, the swine flu (H₁N₁) in 1997, The Ebola virus in 1976 and 1995–1996, the Nipah virus in 1998, and COVID-19 in 2020 [1]. Anticipation steps need to be prepared, considering the possibility of a similar occurrence in the future [2]. Health workers must wear personal protective equipment (PPE) to reduce the risk of contracting or transmitting diseases caused by highly contagious viruses, such as COVID-19 [3,4]. The PPE ensemble must provide encapsulation to isolate health workers from patients, ensuring that it has about twice the evaporation resistance compared to standard medical scrubs [3]. PPE materials are made of materials that do not absorb water, are not water permeable, and are not air permeable, so they cannot transfer heat and sweat from the body to the environment (Troynikov et al., taken from [5]).

Tropical climates are characterized by environmental conditions with warm to hot temperatures throughout the year and high air humidity [6]. Work activities using PPE in a hot and humid environment will significantly increase body heat [7], which harms health and reduces worker productivity [3]. Working in a hot and humid work environment also has the potential to decrease efficiency, increase accidents [8–11], and cause users

to become irritable, restless, and have difficulty concentrating [7,8]. The body's reaction to reduce heat by increasing blood circulation on the surface of the human body causes reduced blood supply to the brain, resulting in decreased concentration [12]. The use of PPE in hot environments causes side effects in the form of thermal discomfort and the emergence of excessive physiological responses [13]. Symptoms of discomfort include increased body temperature, profuse sweating, sweat-soaked clothing, difficulty breathing, anxiety, headache, weakness, fatigue, disruption of movement, and difficulty changing clothes [8,14,15]. The cause of discomfort can be attributed to activities while using PPE in a work environment with a temperature of 30 °C, resulting in a microclimate temperature close to 34 °C and with relative humidity reaching 100% [13].

Several studies have attempted to improve the thermal discomfort experienced by individuals wearing PPE ensembles for COVID-19 treatment. Research by Wang et al. [16] conducted in several major cities in China shows that efforts are needed to reduce the occurrence of heatstroke when wearing impermeable PPE. Recommendations include shifting schedules every 2 h for indoor workers, limiting outdoor workers' PPE usage to less than 2 h, advising workers who work for 8 h to use a personal cooling system with a cooling power $\geq 194.8 \text{ W/m}^2$, or ensuring that workers in the testing booth have access to air conditioners set to 25.0 °C, with a RH of 50–65% and a wind speed of 2.5 m/s. Although this research is very interesting, some adjustments are needed because the climate in China is sub-tropical, whereas the climate in Indonesia is tropical. The high air humidity in the microclimate between the body and clothing has been addressed using a superabsorbent composite layer on the PPE fabric [17]. The superabsorbent composite layer successfully reduces microclimate humidity; however, it causes the PPE fabric to become thick, which inhibits heat transfer to the environment. Cooling wear, in the form of phase change material (PCM) cooled vests, has been used to reduce the risk of thermal strain [18–20]. However, in both research studies, the thick material is a barrier to transferring heat and sweat vapor from the body to the environment. Another study developed an airflow-based cooling device that regulates temperature and air velocity in the microclimate between the skin and PPE to improve thermal comfort while wearing PPE [21–23]. However, these studies have several weaknesses. Firstly, the source of clean air that is being circulated cannot be ascertained because sterilization of the airflow using UV lamps takes place quickly. Secondly, the device is not truly portable because it still uses a large compressor. Lastly, although the design has been developed, it has not been tested on humans who use PPE [23].

Based on the above facts, further research is needed to reduce the discomfort associated with using PPE [8,16]. This research is necessary to ensure wearing comfort for PPE users without compromising its protective function so that health workers can work more productively and avoid errors. This research offers two alternative solutions. The first solution involves the use of breathable cooling wear in the form of a vest made of mesh fabric with 23 °C PCM. Vests made of mesh fabric are expected to not inhibit the transfer of heat and water vapor from the microclimate between the body and clothing to the microclimate between underwear and PPE. The second solution involves the use of a portable airflow cooling device that delivers clean and conditioned air at 23–27 °C to create air circulation that transfers heat and sweat vapor from the microclimate to the environment through convection and evaporation. Airflow to the microclimate also creates positive pressure, which adds to the protective function of PPE. This study aimed to evaluate the discomfort and physiological responses associated with the use of PPE ensembles equipped with breathable cooling wear and portable airflow cooling devices, with the objective of demonstrating the success of these interventions.

2. Materials and Methods

2.1. Participants

Twelve participants, consisting of students and laboratory technicians from one of the universities in Bandung, were randomly selected. The participants had an average age

of 25.17 ± 5.94 years and a BMI of 22.03 ± 2.26 kg/m². The participants were selected randomly to avoid bias and ensure a normal distribution. The participants were confirmed not to have severe diseases, such as heart disease, high blood pressure, diabetes, high cholesterol, and other abnormalities. The participants were asked to sleep at least 5 h at night and have a light breakfast in the morning before the experiment. The participants were given a thorough explanation of the requirements of their participation and were asked to fill out a consent form after agreeing to it. The participants were required to perform the laboratory experiment three times using regular PPE, PPE + a cooling device, and PPE + cooling wear. The participants performed activities such as walking on a treadmill (three times), completing logic-based puzzles (twice), and performing a manual dexterity task (once), with each activity lasting 9 min. After each activity, their perceived comfort and physiological responses were measured. This study received “Ethical Clearance” from the Research Ethics Commission of the Institut Teknologi Bandung with Number KEP/II/2022/X/M071222TT/APDB.

2.2. Materials

The PPE ensemble included a medical coverall, head cap, N95 mask, latex gloves, goggles, face shield, rubber boots/shoes with shoe protection, and a medical uniform. The PPE ensembles evaluated were as follows: (1) Regular PPE ensemble as a control (Figure 1), (2) PPE ensemble plus breathable cooling wear (cooling wear), and (3) PPE ensemble plus a portable airflow cooling device (cooling device).



Figure 1. Regular PPE ensemble.

2.2.1. Portable Airflow Cooling Device

Portable airflow cooling devices (Figure 2) circulate clean, conditioned air into the microclimate to reduce the temperature and humidity of the microclimate and carry heat and sweat vapor to the environment through convection and evaporation mechanisms (Figure 3). The device is designed with several parameters that can be adjusted as needed and has specifications as detailed in Table 1.

The mechanism of the cooling device (Figure 3) is as follows: The incoming air is first filtered using an N-95 mask and an ultraviolet lamp type c (UVC) to remove any viruses and to ensure the air is clean. The clean air is then cooled through a thermoelectric cooler (Peltier) and is subsequently blown into the microclimate that exists between the medical uniform and the coverall using a blower. The supply of air to the microclimate creates positive pressure, which in turn creates a circulation that brings hot and humid air into the environment. The temperature of the air is regulated by a thermostat set between 23–27 °C, and the airflow volume is maintained at 50 L/min [21].

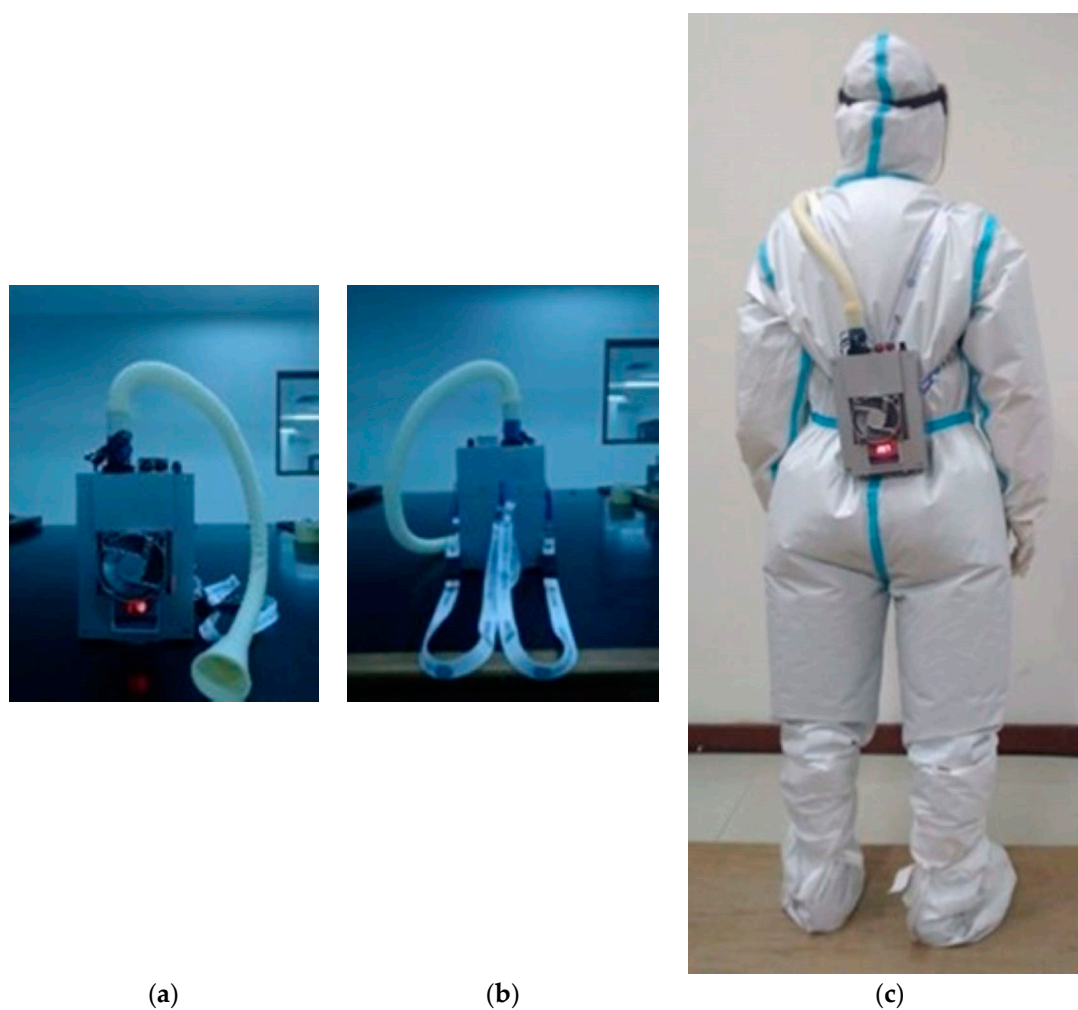


Figure 2. Prototype of the portable airflow cooling device. (a) Front view; (b) back view; (c) PPE application.

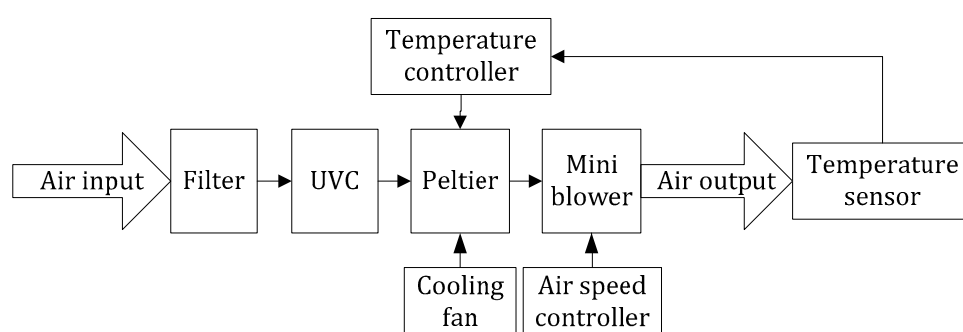


Figure 3. Working scheme of the portable airflow cooling device.

Table 1. Specifications of the cooling device.

Parameters		Specifications
Total weight:		1408.7 g
Diameter of flexible pipe:		2.4 cm
Box dimensions	length:	21.0 cm
	width:	14.6 cm
	thick:	6.2 cm
Battery capacity:		16,000 mAh
Airflow rate:		0–300 L/min (can be adjusted as needed)
Air temperature:		0–30 °C (can be adjusted as needed)
Tool usage time:		4 h

2.2.2. Breathable Cooling Wear

The PCM pack was attached to a vest made of mesh fabric (Figure 4) to cool the microclimate between the medical uniform and the coverall. The mesh fabric facilitates the transfer of heat and sweat vapor from the body to the microclimate. This vest was designed to be adjustable in size as needed and its specifications are detailed in Table 2.

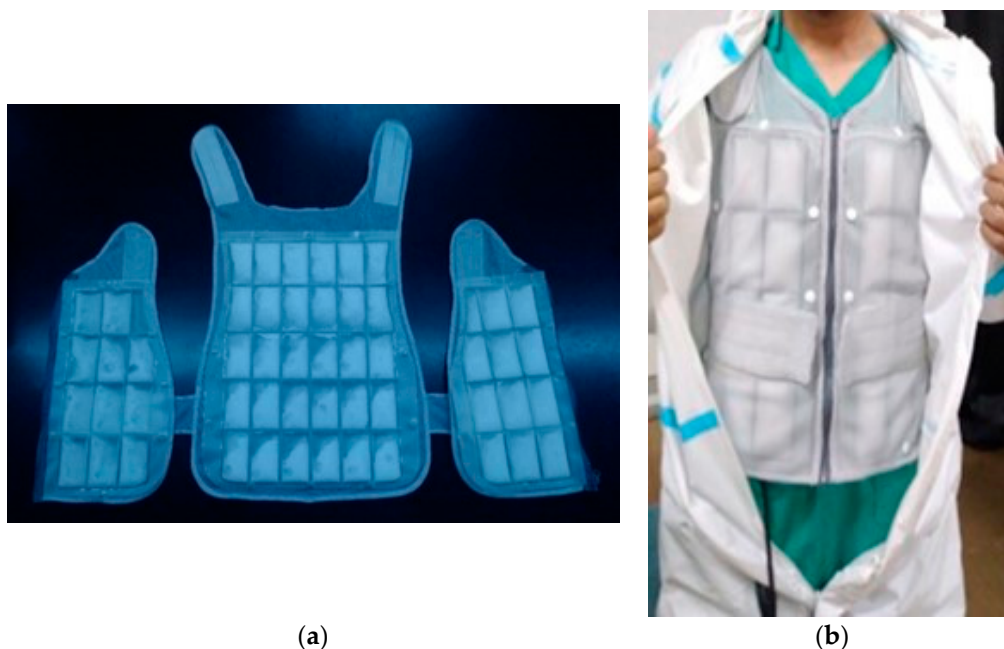


Figure 4. Prototype of the breathable cooling wear. (a) PCM cooling vest with mesh fabric material; (b) PCM cooling vest application.

Table 2. Specifications of cooling wear.

Specifications of Mesh Fabric		Specifications of Vest	
Fabric type:	warp knitting	Material:	polyester
Yarn type:	multi filament	Total weight:	1524 g
Fiber composition:	polyester	Weight of vest:	175 g
Fabric grammage:	187.5 g/m ²	Weight of PCM packs:	1349 g
Thickness of fabric:	0.65 mm	Number of PCM packs:	Frontside: 24 packs Backside: 30 packs
Fabric width:	120 cm	Temp. change phase:	23 °C
Hole size:	2 mm × 2 mm	Size	Adjustable
Number of holes:	(7.5 × 9) holes/inch ²		

The mechanism of cooling wear (Figure 4) is as follows: The PCM Cooling Pack 23 °C changes phase from solid to liquid at 23 °C and, at the same time, absorbs heat energy to reduce the microclimate temperature between the body and the clothing. The decrease in microclimate temperature accelerates the transfer of heat from the body.

2.3. Experimental Design

This study aimed to determine the effect of using breathable cooling wear and portable airflow cooling devices on PPE for virus handling on user comfort and physiological responses. The conditions of the research room, which were designed to replicate the tropical climate in Indonesia, included a temperature of 30 ± 2 °C and a relative humidity of $50 \pm 10\%$ [6]. The experimental protocol was designed with light workloads ranging from 40 to 50 W and medium workloads ranging from 50 to 100 W [24]. The experiment was conducted using a cross-sectional approach and within-subject design (repeated measures), with three tests with three different PPE ensembles. The participants were organized according to a randomized crossover design [11] and each participant underwent experiments at intervals of at least one week to mitigate the influence of adaptation and previous training. The experimental protocol included preparation and physical effort (1 h) that represented the activities of health workers at work. The experimental protocol was developed based on the experiments of Choudhury et al. [25] and Luze et al. [18] and consisted of physical activity with some adjustments, such as the type of activity and the duration of work. Before collecting the data, the participants rested (in the laboratory area), took a second break in the laboratory (20 min), wore complete PPE for 30 min, and then performed six activities for 9 min each, with a rotation time of 1 min (Figure 5). The walking speed on the treadmill was set to a low speed [26,27]. Parameter measurements were taken during the transitions between activities in the experimental protocol. The experiment was conducted at the Laboratory of Work Systems Engineering and Ergonomics, Faculty of Industrial Technology, Institut Teknologi Bandung, between 9:00 a.m. and 4:00 p.m.

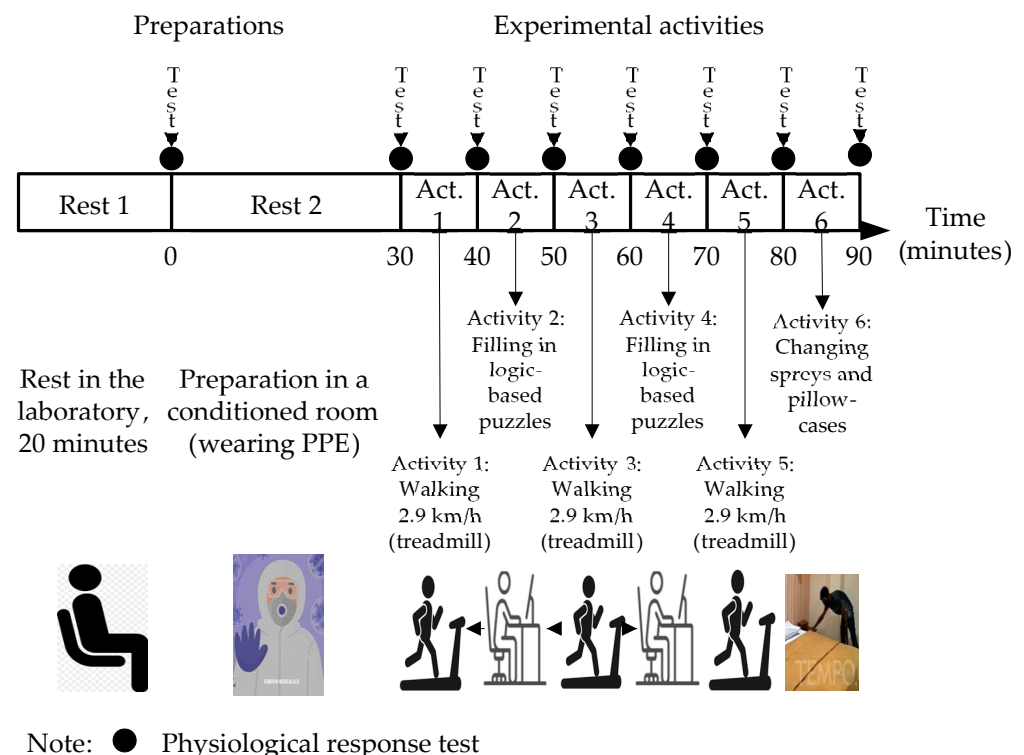


Figure 5. Experimental procedure.

The measured impacts consisted of discomfort parameters, as indicated by a categorical scale with seven points for thermal discomfort sensation (3: very comfortable,

2: comfortable, 1: somewhat comfortable, 0: neutral, −1: slightly uncomfortable, −2: uncomfortable, and −3: very uncomfortable), and seven points for wetness discomfort sensation (3: very dry, 2: dry, 1: somewhat dry, 0: neutral, −1: slightly wet, −2: wet, and −3: very wet) [28,29]. The physiological parameters included core body temperature (temperature at the ear canal) and skin temperature (at 4 points, i.e., neck, right scapula, left hand, and right calf). Skin temperature (T_{sk}) was calculated using the following formula: (T_{sk}) = $0.28 T_{neck} + 0.28 T_{right\ scapula} + 0.16 T_{left\ hand} + 0.28 T_{right\ calf}$). These temperatures were measured using a Beurer FT65 Digital thermometer (Beurer, Ulm, Germany) [30]. Oxygen consumption and heart rate were measured using a VO2 Master Pro type 1.4.0 (VO2 Master, Vernon, BC, Canada). Blood pressure was measured using an Omron digital hem 8712 brand sphygmomanometer (Omron Corporation, Kyoto, Japan). Sweat intensity was determined based on body mass loss which was measured before and after the experiment using an Omron brand scale, Karada Scan Body Composition Monitor HBF-375 (Omron, Kyoto, Japan), and sweat on clothing was measured using a Henherr Electronic Balance BL H2 (Henherr, Taiwan). The temperature and humidity of the microclimate room were measured on the right chest using a thermohygrometer, specifically the SATO model SK-L200TH (Sato Keiryoki Mfg. Co., Ltd., Tokyo, Japan). The instruments used for measurement are described in Table 3.

Table 3. Details of the instruments used in this study.

Parameter	Picture	Merk/Type	Range	Accuracy
Core body temperature Skin temperature		Digital Beurer FT65	34–43 °C	±0.2 °C
Oxygen consumption Heart rate		VO2 Master Pro type 1.4.0	3–250 L/min 0–300 bpm	±1% ±1 bpm
Blood pressure Heart rate		omron digital hem 8712	0–299 mmHg 40–180 bpm	±3 mmHg ±5%
Weight loss		OMRON, Karada Scan Body Composition Monitor HBF-375	0.1–200 kg	±0.4 kg
Sweat on clothing		Henherr BL H2	0–2000 g	±0.01 g

Table 3. Cont.

Parameter	Picture	Merk/Type	Range	Accuracy
Temperature		SATO model: SK-L200TH	−10 to 60 °C 20 to 98%	±0.1 °C
Humidity				±0.1%

2.4. Analysis

Statistical analysis included a data normality test (Kolmogorov–Smirnov test), a data uniformity test (Levene test), a one-way repeated measures analysis of variance (one-way ANOVA) across three PPE ensemble conditions, and an analysis of differences between the means of each treatment (Bonferroni post-hoc test). If normality and/or uniformity of the data could not be confirmed, a variance analysis using the Kruskal–Wallis test was used. A value of $p = 0.05$ was used as the limit of statistical significance.

3. Results

The results of the statistical analysis of the experimental data are presented as follows:

3.1. Temperature and Humidity Microclimate between the Body and Clothing

The addition of cooling wear and cooling devices to the PPE ensemble reduced the microclimate temperature and humidity ($p = 0.000$) compared to without cooling (Figure 6). There was a significant difference in microclimate temperature between regular PPE compared to PPE + cooling wear and PPE + the cooling device. However, there was no significant difference in microclimate temperature between PPE + cooling wear and PPE + the cooling device. Statistically significant differences also occurred in microclimate air humidity between sole PPE and PPE + cooling wear compared to PPE + the cooling device. However, there was no significant difference in microclimate temperature between sole PPE and PPE + cooling wear.

The use of cooling wear in the form of a PCM-cooled mesh fabric vest with a phase change point of 23 °C successfully absorbed the heat that occurred to reduce the microclimate temperature by 3.66 °C. The cooling device circulates clean conditioned air at 23–27 °C into the microclimate and carries heat to the environment, thus reducing the microclimate temperature by 2.86 °C. There is a different pattern in the PPE microclimate temperature graph with the addition of cooling wear and cooling devices (Figure 6a). The microclimate temperature in PPE, with the addition of cooling wear, starts from a low temperature and continues to increase along with PCM phase change. The microclimate temperature in PPE with the addition of a cooling device starts at a high temperature and continues to decrease as the effectiveness of low-temperature airflow and the transfer of sweat vapor and heat from the microclimate to the environment take effect. The use of cooling wear and cooling devices for PPE reduced microclimate humidity between the body and clothing. The use of cooling devices effectively reduced microclimate humidity by 27.92%. Conditioned clean airflow successfully carried sweat vapor and body heat to the environment by convection and evaporation. The use of cooling wear only succeeded in reducing microclimate humidity by 5.33% (a statistically insignificant decrease) because sweat vapor was retained in the microclimate between the body and clothing, which has high water vapor resistance (impermeable).

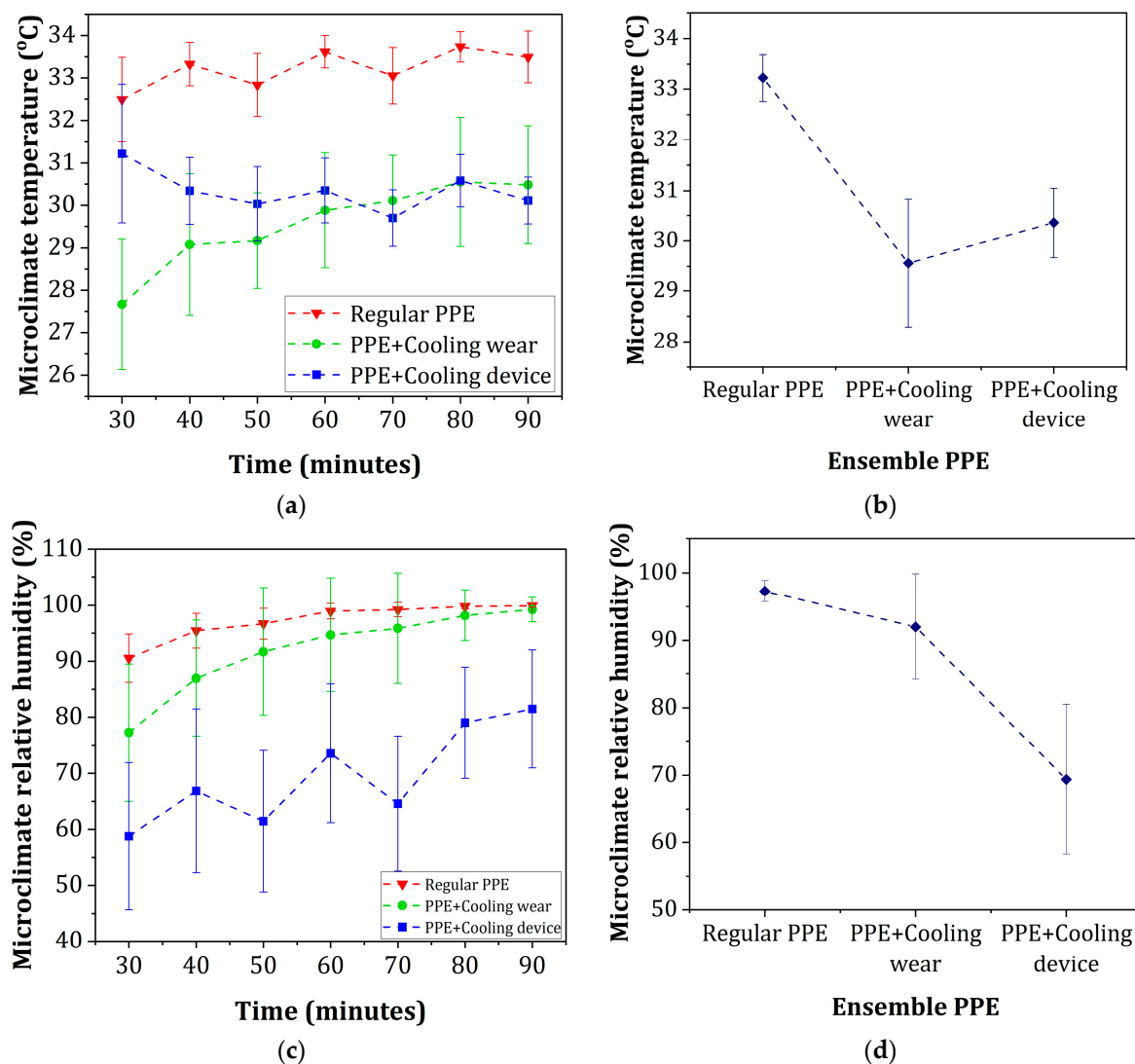


Figure 6. Relationship between the addition of cooler and microclimate temperature and humidity. (a) Activity time with microclimate temperature; (b) the addition of cooler with microclimate temperature; (c) activity time with microclimate relative humidity; (d) the addition of cooler with microclimate relative humidity.

3.2. Heat and Wetness Discomfort Sensation

The addition of cooling wear and cooling devices to the PPE ensemble increased the comfort sensation of heat ($p = 0.000$) and wetness ($p = 0.000$) compared to using no cooling mechanisms (Figure 7). The mean discomfort sensation of heat increased from -2.04 and wetness from -2.15 (without cooling) to -0.15 and -0.63 (with the addition of cooling wear), respectively, and -0.14 and -0.37 (with the addition of a cooling device), respectively. This trend was observed from the beginning to the end of the activity (Figure 7). The discomfort sensation of heat and wetness in sole PPE was significantly different compared to PPE equipped with cooling wear and cooling devices. The use of cooling wear and cooling devices succeeded in increasing the sensation of hot and wet comfort. This was in accordance with the analysis in point 3.1, indicating that the use of coolers, especially cooling devices, succeeded in reducing the temperature and humidity of the microclimate between the body and clothing. These effects were directly felt by PPE users.

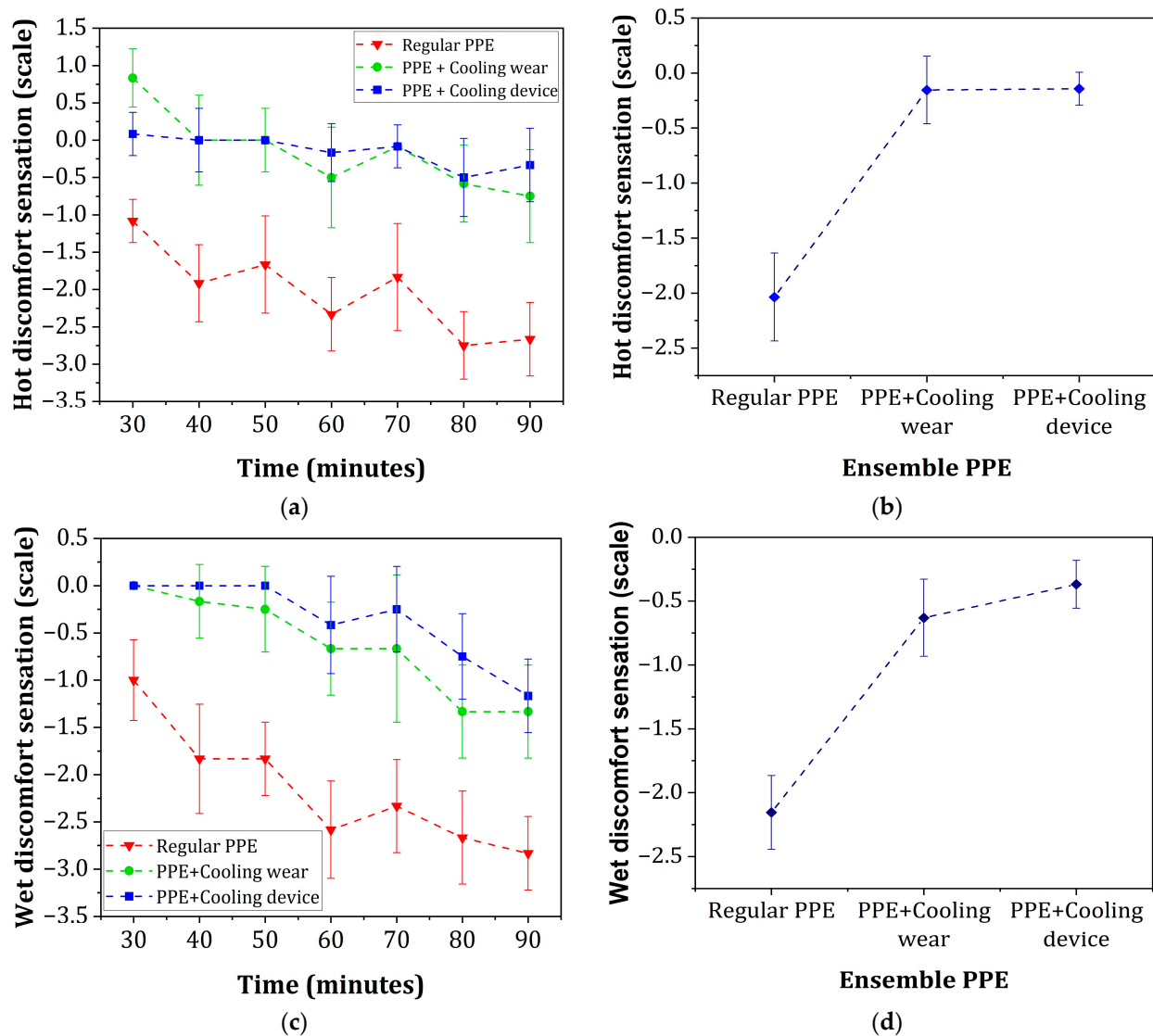


Figure 7. Relationship between the addition of a cooler and the sensation of hot and wet discomfort. (a) Activity time with hot discomfort sensation; (b) the addition of a cooler with hot discomfort sensation; (c) activity time with wet discomfort sensation; (d) the addition of a cooler with wet discomfort sensation.

3.3. Core Body Temperature and Skin Temperature

The addition of cooling wear and cooling devices to the PPE ensemble was able to reduce core body temperature ($p = 0.000$) and skin temperature ($p = 0.000$) compared to without cooling (Figure 8). The mean core body temperature dropped from 37.98°C and skin temperature dropped from 36.85°C (without cooling) to 37.81°C and 36.71°C (with the addition of cooling wear), respectively, and 37.49°C and 36.07°C (with the addition of a cooling device), respectively. This trend was observed from the beginning to the end of the activity. There was a significant difference in core body and skin temperature between the use of sole PPE and PPE + cooling wear compared to PPE + a cooling device, and there was no significant difference between the use of sole PPE and PPE + cooling wear. The low temperature and humidity of the microclimate facilitates the transfer of metabolic heat from the body to the microclimate, resulting in lower skin and core body temperatures compared to conditions without cooling. A decrease in skin temperature and core body temperature increases the sensation of heat comfort. In addition, a decrease in core body temperature and skin temperature reduces sweat production, which increases the sensation

of wet comfort. Airflow-based cooling devices reduce core body and skin temperatures more effectively than cooling wear. This occurs because of its ability to circulate cold air into the microclimate, carry sweat vapor and body heat into the environment, and reach almost the entire body, whereas cooling wear only covers the front and back of the body.

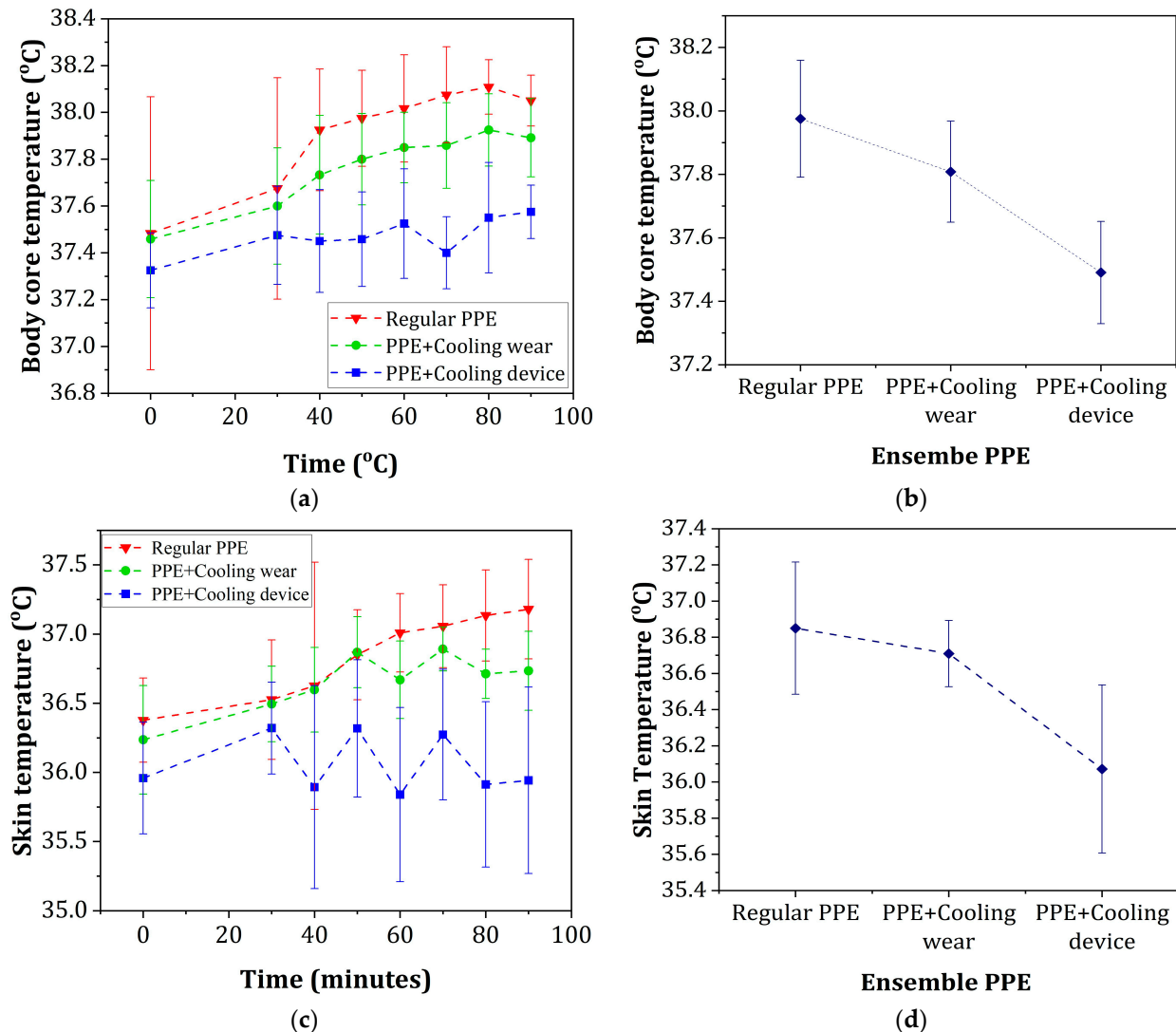


Figure 8. Relationship between the addition of cooler and core body and skin temperature. (a) Activity time with core body temperature; (b) the addition of a cooler with core body temperature; (c) activity time with skin temperature; (d) the addition of a cooler with skin temperature.

3.4. Oxygen Consumption

According to the experimental protocol, adding cooling wear and cooling devices had no significant effect on oxygen consumption ($p = 0.260$) during the activities (Figure 9). This could be due to the experimental protocol, which involved activities that imposed the same workload across each experiment. Oxygen consumption is influenced by work activity. Work activities require energy generated from the body's metabolism. The body's metabolism requires oxygen, so if the activities performed are the same, the oxygen demand is also the same. The experimental protocol also involved a light to moderate workload. The existence of acclimation before the experiment made respondents adapt physiologically to the environment. The use of N95 masks limits the amount of oxygen consumed during activities, so oxygen consumption is lower [25,31].

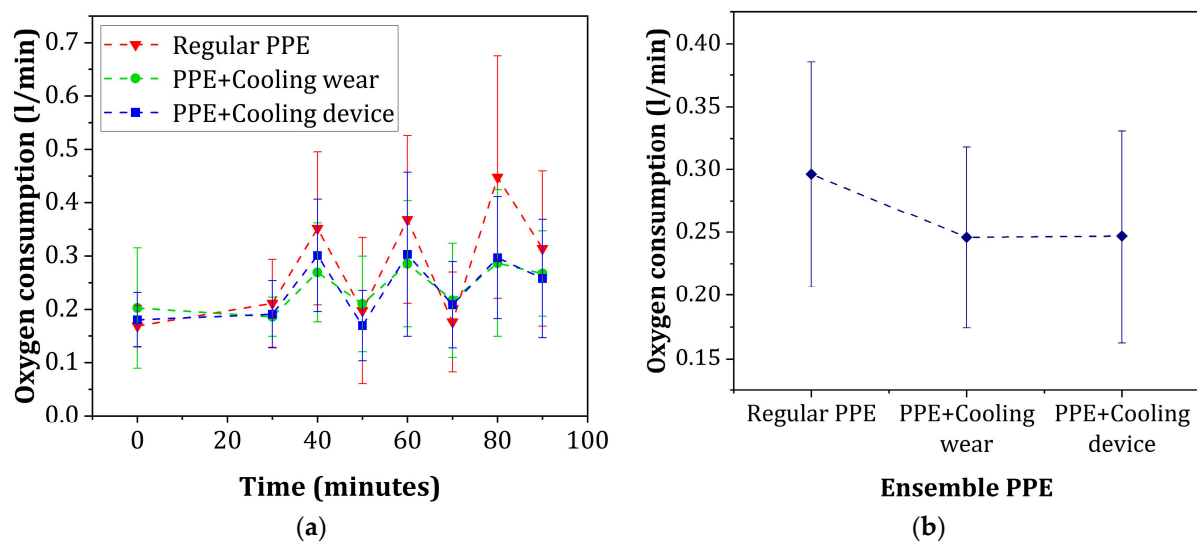


Figure 9. Relationship between the addition of cooler and oxygen consumption. (a) Activity time with oxygen consumption; (b) the addition of a cooler with oxygen consumption.

3.5. Heart Rate and Blood Pressure

The addition of cooling wear and cooling devices to the PPE ensemble successfully reduced heart rate ($p = 0.042$) and systolic blood pressure ($p = 0.002$) compared to conditions without cooling; however, diastolic blood pressure exhibited no significant change ($p = 0.694$) compared to conditions without cooling (Figure 10). Mean heart rate decreased from 120.25 bpm with the use of sole PPE to 106.85 bpm (with the addition of cooling wear) and 102.06 bpm (with the addition of a cooling device). Mean systolic blood pressure decreased from 123.34 mmHg with the use of sole PPE to 115.55 mmHg (with the addition of cooling wear) and 111.60 mmHg (with the addition of a cooling device). This trend was observed from the beginning to the end of the activity (Figure 10a,c). There was a significant difference in heart rate and systolic blood pressure between sole PPE and PPE + the cooling device. However, there were no significant differences between sole PPE compared to PPE + cooling wear and between PPE + cooling wear compared to PPE + the cooling device. Based on heart rate, the peak load during activities with sole PPE at an ambient temperature of 30 °C was categorized as a heavy workload (130–150 bpm). The addition of cooling wear and cooling devices to the PPE ensemble succeeded in reducing the workload to a moderate workload (100–130 bpm). This occurred because the use of cooling wear and cooling devices succeeded in reducing body core temperature and skin temperature. Blood pressure and heart rate decreased as the need for blood flow to the skin to cool the body decreased. Diastolic blood pressure was not affected by the addition of cooling wear and cooling devices because changes in diastolic blood pressure are relatively smaller than changes in systolic blood pressure [24].

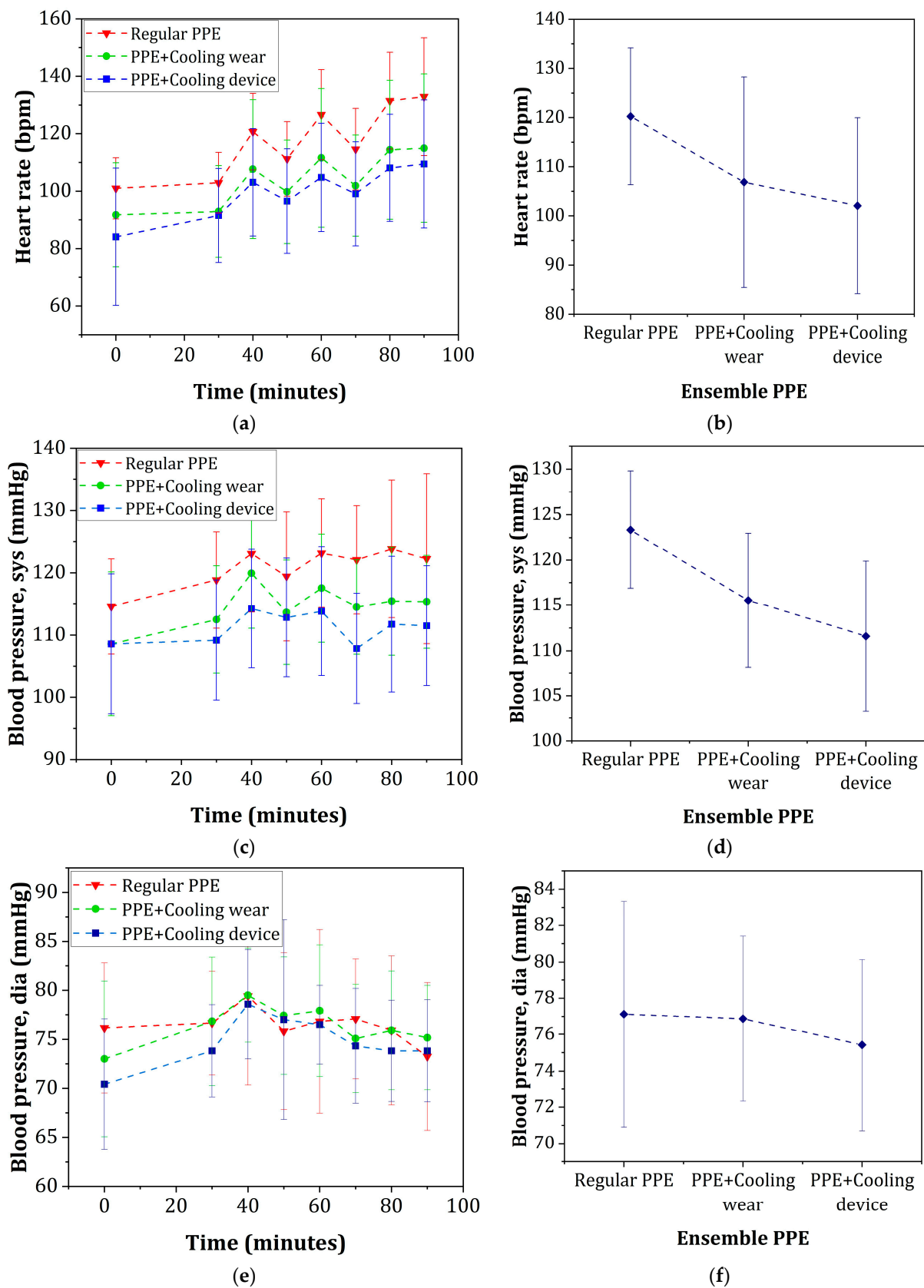


Figure 10. Relationship between the addition of cooler and heart rate and blood pressure. (a) Activity time with heart rate; (b) the addition of a cooler with heart rate; (c) activity time with systolic blood pressure; (d) the addition of a cooler with systolic blood pressure; (e) activity time with diastolic blood pressure; (f) the addition of a cooler with diastolic blood pressure.

3.6. Weight Loss and Sweat on Clothing

The addition of cooling wear and a cooling device to the PPE ensemble reduced weight loss ($p = 0.000$) and sweat on the clothes ($p = 0.001$) compared to conditions without cooling (Figure 11). Average weight loss decreased by 425.00 g (without cooling), 216.67 g (with the addition of cooling wear), and 200.00 g (with the addition of a cooling device). This trend aligns with the decrease observed in the average amount of sweat on clothing, which was 140.08 g (without cooling), 71.55 g (with the addition of cooling wear), and 37.25 g (with the addition of a cooling device). There was a significant decrease in weight loss and sweat on clothes with the use of sole PPE compared to PPE + cooling wear and PPE + the cooling device, and there was no significant difference between PPE + cooling wear and PPE + the cooling device. The use of cooling wear and cooling devices in the PPE ensemble successfully enabled metabolic heat transfer to the microclimate, even with airflow-based cooling devices successfully transferring heat and sweat vapor through convection and evaporation. This can be seen from the decrease in temperature and humidity within the microclimate between the body and clothing.

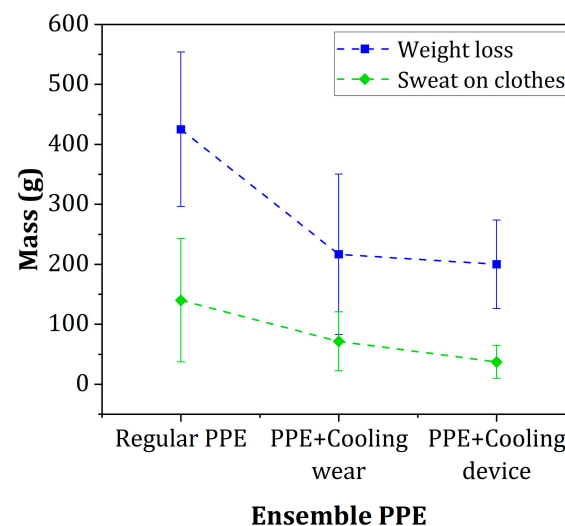


Figure 11. Relationship between cooler and weight loss and sweat on clothes.

4. Discussion

This study's results are better than those of Hu et al. [20]. Cooling wear significantly increased the sensation of thermal comfort. The addition of cooling wear to the PPE ensemble at a working environment temperature of 30 °C was able to significantly increase the sensation of thermal comfort by 1.9 scales (−2.04/very uncomfortable to −0.14/near neutral), whereas phase change material cooling clothing (PCM-CC) in a thermal environment with a temperature of 32 °C [20] increased thermal comfort by 1.25 scales (−1.33/uncomfortable to −0.08/near “neutral”). Cooling wear managed to reduce skin temperature by 0.14 °C, whereas wearing PCM-CC reduced the average skin temperature by 0.65 °C. The use of PCM-CC reduces skin temperature greater than in this study. This is because the cold temperature of PCM is lower (21 °C) and is retained by the thick vest. The advantage of this study lies in the use of a vest made of mesh fabric, whereas the study conducted by Hu et al. [20] used a tighter and thicker fabric. The use of cooling wear and cooling devices in this study yielded superior results compared to the research conducted by Zhao et al. [23]. This study succeeded in reducing skin temperature by 0.14 °C (with the addition of cooling wear) and 0.78 °C (with the addition of a cooling device), whereas the research conducted by Zhao et al. [23] reduced skin temperature by 0.61 °C (with the addition of cooling wear) and 0.22 °C (with the addition of a cooling device). Heart rate was successfully reduced by 13.39 bpm (with the addition of cooling wear) and 18.19 bpm (with the addition of a cooling device), whereas in the research conducted by Zhao et al. [23], heart rate was reduced by

10.7 bpm (with the addition of cooling wear) and 8.5 bpm (with the addition of a cooling device). Cooling wear in this study resulted in a lesser reduction in skin temperature compared to the research conducted Zhao et al. [23] because that research used ice bags with very low temperatures. The use of cooling devices in this study was better because the air supplied to the microclimate was conditioned at 23–27 °C, whereas in the study conducted by Zhao et al. [23], the air supplied to the microclimate was air from the working environment conditions (without conditioning).

Limitations. This research proves that the addition of cooling wear and cooling devices to the PPE ensemble can improve comfort and reduce the physiological response of PPE wearers handling highly contagious viruses in the tropics. However, in this experiment, we recruited students and laboratory technicians. Future research should recruit health workers who directly use complete PPE and work with patients with highly contagious viral diseases. Matching the PPE ensemble with the respondents recruited for the trial will lead to more accurate evaluation results. The research results can still be developed to increase the comfort of using cooling wear and cooling devices. First, the PCM cooling pack packaging is still united in three panels, so it may still hinder the transfer of heat and sweat vapor from the body to the microclimate environment. Further development may involve dividing the PCM cooling pack packaging into several parts per panel. Second, the weight of the cooling device can be reduced. One source of the weight comes from the number of batteries installed (to achieve a 4-h usage time). Further development may involve dividing the battery into two parts (part of the battery installed in the cooling device and part of it becoming a spare battery that can be used to recharge the device). When the installed battery runs out, it can be easily replaced with the fully charged spare battery.

5. Conclusions

The results show that adding cooling wear and cooling devices to the PPE ensemble significantly affects comfort and physiological responses, which is better than in previous research. The addition of cooling wear can significantly reduce the microclimate temperature, skin temperature, core body temperature, blood pressure (systolic), and sweat intensity, and improve the sensation of hot and wet comfort. The addition of cooling wear does not significantly affect microclimate humidity, heart rate, diastolic blood pressure, and oxygen consumption. The addition of cooling devices can significantly reduce microclimate temperature and humidity, skin temperature, core body temperature, heart rate, blood pressure (systolic), and sweat intensity, and improve the sensation of hot and wet comfort. The addition of cooling devices does not significantly affect diastolic blood pressure and oxygen consumption. It can be concluded that the addition of cooling wear and cooling devices to the PPE ensemble can reduce workload by 13.00% and 17.82%, respectively. The workload changed from the heavy load category to the medium load category. There is a similarity in the pattern of subjective perception assessments (the sensation of heat and wet comfort) with the results of objective measurements (physiological responses) and workload. When comparing the two interventions, it can be concluded that cooling devices have a better effect on the comfort of using PPE ensembles compared to cooling wear.

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