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Cooling performance measurements of different types of cooling vests using thermal manikin

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Abstract

This study compared the effectiveness of five commercially available cooling vests using three distinct thermal manikin test protocols. In addition, the constraints associated with each test protocol were elucidated, facilitating the identification of suitable evaluation methods for the different cooling vests. The cooling performances of the vests were evaluated using three thermal manikin test scenarios, incorporating the adaptations from Ciuha et al. (Ergonomics 64:625–639, 2021) and ASTM F2371-16, along with a modified protocol simulating the hot and humid weather in a South Korean summer. The results revealed substantial variations in the cooling performance across different test protocols, highlighting the importance of carefully selecting thermal manikin test methods. Moreover, the specific cooling vests exhibited immeasurable performance in certain test methods, which presents the limitations inherent in each testing scenario. For example, when evaluated with a non-sweating thermal manikin, the air-cooling vests exhibited the worst cooling performance, showing an average cooling rate of 1.0 W and cooling durations of five minutes. In contrast, the same vests demonstrated superior performance when assessed using the ASTM F2371-16 method, revealing an effective cooling rate of 114.8 W and sustained cooling durations exceeding eight hours. These results emphasize the lack of a one-size-fits-all evaluation method for cooling vests and the need for accessible guidelines to inform decision-makers aiming to enhance workplace safety and comfort.

Keywords: Personal cooling system, Auxiliary cooling system, Cooling vest, Thermal manikin, Occupational heat stress

Introduction

The hot and humid summer season in South Korea carries a substantial risk of heat stress, contributing to preventable fatalities in various industries. Personal cooling systems, especially in the form of cooling vests, are considered a practical, applicable, and effective measure to alleviate the heat strain for the working population, particularly in cases where behavioral thermoregulation, such as adjusting clothing layer, physical activity, or environmental conditions cannot be an accessible strategy because of the restrictions of the occupational setting (Barr et al., 2009; Taylor et al., 2021). Numerous commercially available options exist for cooling vests operated based on various

cooling mechanisms (e.g., liquid-cooling vest, fan-cooling vest, phase-change materials, and hybrid cooling vest) (Golbabaei et al., 2022; Taylor et al., 2021; Yazdi & Sheikhzadeh, 2014). In recent years, developments in thermoelectric conductive cooling using a Peltier module have been prominent (Tabor et al., 2020), but further improvements in the weight and flexibility of electrical components are needed before they can be of practical use. Hence, a valid question remains from the users' perspective: which cooling vests would be the most suitable for their occupational environment? Workers' heat strain can be alleviated by selecting a proper cooling vest. An ineffective cooling vest may become a physical and physiological burden because it adds a clothing layer and weight, increasing thermal insulation and forming a barrier for the evaporation of sweat from the body (Chan et al., 2016; Ciuha et al., 2021). Therefore, conducting a performance evaluation of cooling vests and comparing them quantitatively and objectively is imperative for decision-makers involved in purchasing and selecting cooling vests.

Human trial tests and thermal manikin tests are used widely to assess cooling vests. The latter, in particular, offers advantages, such as a more straightforward test procedure with acceptable reproducibility and repeatability of the outcomes. This has led to the widespread use of thermal manikin tests to evaluate the cooling vest performance despite their limitations in simulating human thermoregulatory responses (Ciuha et al., 2021; Lu et al., 2015; Miura et al., 2017; Yi et al., 2017). Ciuha et al. (2021) developed a cooling vest evaluation protocol using a thermal manikin. They proposed an eight-hour protocol to measure the actual cooling duration and resulting cooling capacity and compared various commercially available vests using different cooling concepts. The test method was carried out under isothermal conditions using a non-sweating thermal manikin that facilitated measurements of the net dry heat loss (convective and conductive heat loss) from the cooling vest. Nevertheless, it could lead to an underestimation of the cooling effectiveness, particularly for air-cooling vests with built-in fans whose performance relies greatly on evaporative heat loss. Unfortunately, the study did not encompass this air-cooling vest with fans.

In contrast, ASTM F2371-16, which is currently the only de facto international standard regarding cooling vest evaluation methods, uses a sweating thermal manikin test protocol in a shorter measurement period. Nevertheless, concerns persist about potential overestimation in hot and humid conditions because it mandates testing under hot and dry conditions, 35 ℃ and 40%RH. In addition, limited research has addressed the applicability of the ASTM F2371-16 standard test to different types of cooling vests. Challenges already emerge when attempting to identify a suitable test method to select a proper cooling vest.

Researchers have a consensus that the effectiveness of cooling vests depends on the vest type, resulting in situations where they can be advantageous in specific environments and less effective in others (Lu et al., 2015; Taylor et al., 2021). For example, the physiological advantages of phase change materials (PCMs) have been prominent in hot and humid environments or when worn beneath protective clothing, where evaporative and convective heat loss may be impractical and restricted (Ciuha et al., 2023; Kenny et al., 2011; Maley et al., 2020). On the other hand, evaporative cooling vests demonstrate optimal efficiency under dry conditions, particularly when combined with a higher air velocity (Ciuha et al., 2023; Rykaczewski, 2020). Cooling vests can be worn on

the clothing ensemble and beneath the outer layer (e.g., firefighters' turnout gear), which depends on the types of cooling vests and the characteristics of protective clothing worn with cooling vests. When the cooling vest is worn in the middle of the clothing layer or between the skin and inner layer, it is surrounded by a microclimate that is more humid than the ambient air, which can lead to evaporative heat loss being blunted (Kim et al., 2014). From the viewpoint of industrial application, the environmental influence on the performance of a cooling vest can be rephrased so that the test results can be distorted and different depending on the selection of the test methods, which may lead to mistaken decisions.

In light of this context, this study assessed the performance of various commercial cooling vests based on three thermal manikin test protocols, including Ciuha et al. (2021), ASTM F2371-16, and a modified ASTM F2371-16, to quantitively demonstrate the limitation of each test protocol so that a suitable test method for each cooling vest type can be suggested. The authors also suggest a practical implication for decision-makers of cooling vests in industrial applications.

Methods

Cooling vests and clothing ensemble

Five commercially available cooling vests using different cooling modes were assessed (Table 1): (1) ACV (air-cooling vest), (2) LCV (liquid-cooling vest), 3) EVAP (evaporative cooling vest), (4) PCM (cooling vest with PCM inserts), (5) Hybrid (evaporative cooling vest with PCM inserts). Air-cooling vests that require an external compression air source connection were excluded, so only the cooling performances of portable products could be compared. The size of all vests was selected to ensure a proper fit on the thermal manikin. Among the vests, the ACV (Active Cooling Vest, Teijin, Japan) featured six built-in fans: four on the lower back and two near the stomach. The battery was fully charged before each test to assess its operational duration over eight-hour protocols. The LCV (CompCooler Univest ICE Water Cooling System (UICS), Compcooling, US) consisted of a vest with embedded water-circulating tubes, a battery, and a two-liter ice pack. This ice pack was connected to the circulating tubes, and ice water was supplied through tubes as the ice melted. Ice packs were removed from the chamber before each test started, and a small amount of water

Table 1 Information on the cooling vests compared in this study

Code	Product name (Company, Country)	Cooling mode	Size	Weight (g)
ACV	Active Cooling Vest (Teijin, Japan)	Air-cooling by battery-powered built-in-fans	Small	1366
LCV	CompCooler Univest ICE Water Cooling System (UICS) (Compcooler, the United States of America)	Liquid-cooling by ice water circulating system	X-Small–Small	4430
EVAP	Bodycool Hybrid (Inuteq, Netherlands)	Evaporative cooling by water absorbed into the vest	Small	232[a)]
PCM	Bodycool Hybrid (Inuteq, Netherlands) with INUTEQ-PAC® PCM cooling inserts having a melting temperature of 15°C	Conductive cooling by PCM inserts		1386[a)]
Hybrid		Evaporative cooling by water absorbed into the vest and conductive cooling by PCM inserts		

[a] The weight of water absorbed by the vest was not considered

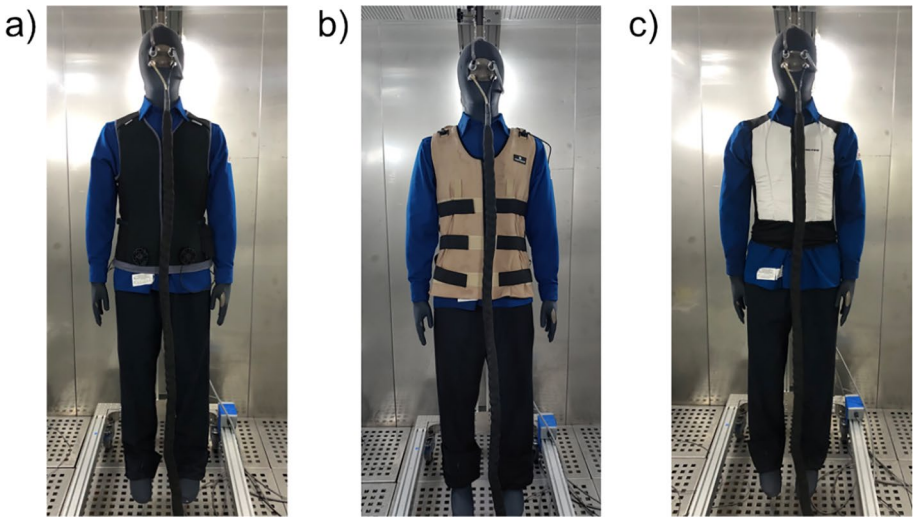

Fig. 1 Thermal manikin wearing an air-cooling vest (**a**), liquid-cooling vest (**b**), and an evaporative cooling vest (**c**). An evaporative cooling vest could also be used with a combination of phase-change material inserts

was poured into the pack for water circulation. EVAP, PCM, and Hybrid were tested using an evaporative vest (Bodycool Hybrid, Inuteq, Netherlands). When evaporative cooling was activated (EVAP and Hybrid), the vest was sufficiently soaked in water at ~ 20 ℃ for at least two minutes and gently squeezed to remove excess water drops. Under PCM conditions, the PCMs were completely solidified and removed from the chamber immediately before each test started. The thermal and evaporative resistance of the cooling vests were not measured, but the values, except for the ACV, are available elsewhere (Ciuha et al., 2021).

In all measurements, the cooling vests were worn over a baseline clothing ensemble composed of a long-sleeved shirt (203 g/m^2, Bulwark, #SND6NV), flame-resistant trousers (203 g/m^2, Bulwark, #PNW3NV), and men's underwear briefs (180 g/m^2, 100% cotton) (Fig. 1). This ensemble was a calibration clothing ensemble demonstrated in ASTM F2370-22. In this study, the ensemble was chosen to simulate working uniforms for workers occasionally exposed to heat and flame (e.g., electrical workers and soldiers).

Thermal manikin

Thermal manikin measurements were conducted with a 34-zone sweating thermal manikin (178 cm in height, 1.81 m^2 in body surface area, Newton, Thermetrics, US) (Fig. 1). The study utilized the constant temperature mode, setting the surface temperature of all segments to 35 ℃ using the ThermDAC® software, which continuously recorded the heat loss for each segment. When the sweating system was used, the manikin wore a water-fed capillary fabric skin covering the entire surface of the manikin, including the head, chest, back, abdomen, buttocks, arms, hands, legs, and feet. Before each sweating test, the manikin surface was pre-wetted with distilled water to simulate sweat-saturated skin with a water spray and heated to stabilize the regional heat flux of the whole body.

Table 2 Environmental conditions and procedures of the thermal manikin test protocols

Protocol	Sweating system	Environmental condition	Reference
A. No_SWT	Not used	35 ℃, 35%RH	Ciuha et al. (2021)
B. SWT_HD	Used	35 ℃, 40%RH	ASTM F2371
C. SWT_HH	Used	35 ℃, 70%RH	Modified ASTM F2371

Test protocols and environmental conditions

The cooling performance of each cooling vest was evaluated using three different test methods: (1) No_SWT, (2) SWT_HD, and (3) SWT_HH (Table 2). Thermal manikin test measurements were carried out under isothermal conditions. In the [No_SWT] method, the sweating system of the thermal manikin was not activated. The environmental chamber was maintained at 35 ℃ with 35% relative humidity (RH) following the experimental setting of Ciuha et al. (2021). No temperature gradient existed between the manikin skin and the surrounding air because the skin temperature of thermal manikin was also set to 35 ℃, which facilitated that only the heat loss resulting from the cooling vest could be measured (Ciuha et al., 2021). The other two conditions, [SWT_HD] and [SWT_HH], were designed according to the experimental procedures of ASTM F2371-16, but the relative humidity of the chamber was the only difference between them. The ambient temperature and relative humidity were 35 ℃ with 40% RH, and 35 ℃ with 70%RH, respectively. The latter was to simulate hot and humid weather. All measurements were carried out for eight hours so that the absolute cooling power and the actual operational time of cooling vests could be measured. The wind speed in the chamber was maintained at below 0.4 ms^{-1}.

Calculation and analysis

The manikin surface temperature, air temperature, relative humidity, and the regional power input to the manikin were recorded every minute throughout the entire

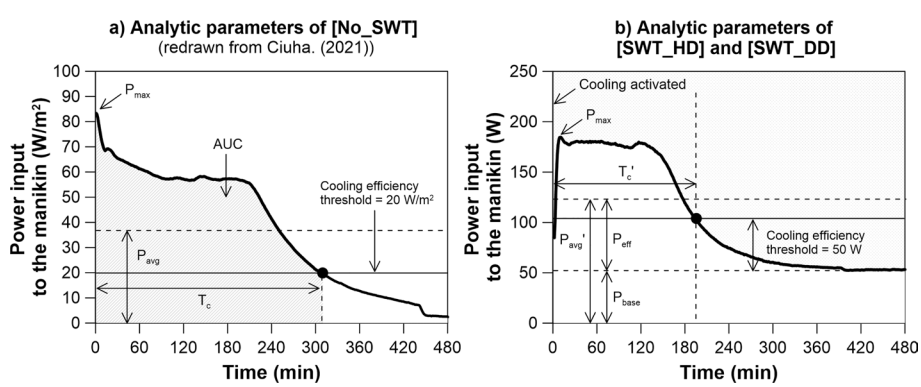

Fig. 2 Graphic presentation of the analytical parameters indicating the cooling performance for each test method: **a** P_{max}: maximal cooling rate; P_{avg}: average cooling rate throughout the eight-hour measurement; T_c: cooling duration when $P \geq 20W/m^2$; AUC: area under the curve, indicating cooling capacity. **b** P_{avg}': average cooling rate during T_c'; P_{eff}: effective cooling rate (P_{avg}'-P_{base}); P_{base}: baseline power input measured with cooling vests not activated; T_c': duration of cooling calculated until the P_{eff} has decreased to 50W

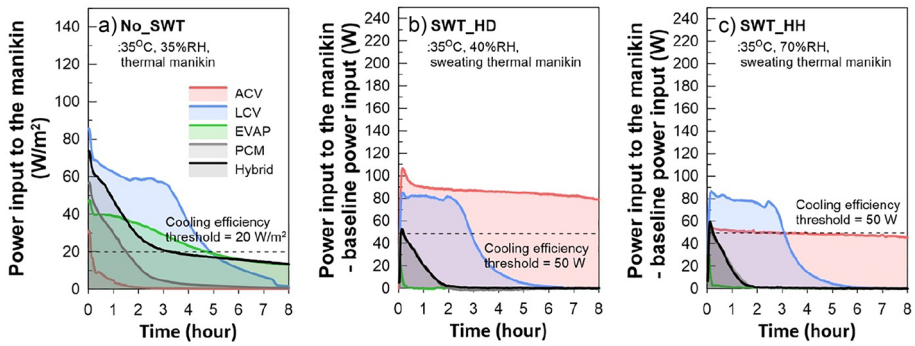

Fig. 3 Comparison of the cooling power according to the protocols for eight hours. The red, blue, green, gray, and black lines represent the results for the *ACV, LCV, EVAP, PCM*, and *Hybrid* vests, respectively, in that order. *ACV* Active cooling vest; *LCV* Liquid-cooling vest; *EVAP* Evaporative cooling vest; *PCM* Vest with phase-change material inserts; *HYBRID* Evaporative cooling vest with phase-change material inserts

protocol. The cooling performance of the cooling vests was assessed using existing the analytic parameters based on Ciuha et al. (2021) for [No_SWT] and ASTM F2371-16 for [SWT_HD] and [SWT_HH], as shown in Fig. 2. Regarding the results of [No_SWT], the maximal cooling rate (P_{max}), average cooling rate (P_{avg}), cooling duration (T_c), and cooling capacity (AUC, area under the curve) were calculated as explained by Ciuha et al. (2021). T_c was defined as the duration between the initial time point of the maximal cooling rate and the final time when the power input reached or exceeded 20 W/m^2. In the case of [SWT_HD] and [SWT_HH], the average cooling rate (P_{avg}') was calculated as the time-weighted average of the power input during T_c', which was determined as the duration from the time the cooling vest was activated until the effective cooling rate decreased to 50W, as suggested in ASTM F2371-16. The effective cooling rate (P_{eff}) was derived by subtracting the average and baseline cooling rates (P_{base}). P_{base} was obtained by averaging at least 30 min from when the cooling vests completely lost their cooling effect.

Results

Among the cooling vests, the ACV showed the most dramatic differences in the time-course curves by the test methods. [No_SWT] showed a very short peak immediately after cooling started, then decreased to 0 W/m^2 despite the cooling fans running continuously (Fig. 3a, described as a red line). On the other hand, In [SWT_HD] and [SWT_HH], when sweating of the manikin was activated, it showed significant advances in cooling power. Moreover, the measured values soon stabilized after drawing a peak after the fans started to run. They were then maintained relatively constant with a slight decreasing trend (Fig. 3b–c). In addition, a prominent difference was observed depending on the relative humidity. In [SWT_HD], all calculated parameters showed greater values (Fig. 3b) than under the hot and humid conditions [SWT_HH] (Fig. 3c) (Table 3).

Unlike the ACV, the cooling performance of the LCV barely differed regardless of the test methods. In all three protocols, the system consistently maintained a relatively elevated and stable value during the initial two to three hours. Subsequently, as the ice melted and the temperature of the circulating water began to decline, there was a marked drop in cooling performance and a complete dissipation of the cooling effect

Table 3 Comparison of the parameters indicating the cooling performance of each cooling vest during three thermal manikin test methods

Test methods	Parameters	ACV	LCV	EVAP	PCM	Hybrid
No_SWT :35°C, 35%RH, Non-sweating thermal manikin	P_{max} (W)	17.9	85.6	46.6	56.7	73.6
	P_{avg} (W)	1.0	35.6	25.3	9.6	25.2
	AUC (W·h)	2.7	256.6	151.8	52.6	123.6
	T_c (min)	5	291	283	89	193
SWT_HD :35°C, 40%RH, Sweating thermal manikin	P_{max} (W)	135.6	117.0	74.7	97.7	99.5
	P_{avg}' (W)	114.8	111.1	*N.A*	86.1	84.2
	P_{base} (W)	29.0	34.4	49.6	46.3	46.6
	P_{eff} (W)	85.8	76.8	*N.A*	39.8	37.6
	T_c' (min)	> 480	172	0	8	11
SWT_HH :35°C, 70%RH, Sweating thermal manikin	P_{max} (W)	67.2	105.1	55.6	77.7	86.3
	P_{avg}' (W)	60.5	93.4	*N.A*	66.5	74.1
	P_{base} (W)	18.0	18.2	26.5	25.0	26.4
	P_{eff} (W)	42.5	75.1	*N.A*	41.6	47.7
	T_c' (min)	114	186	0	10	14

ACV air-cooling vest; *LCV* liquid-cooling vest; *EVAP* evaporative cooling vest; *PCM* cooling vest with PCM inserts; *Hybrid* evaporative cooling vest with PCM inserts; P_{max} maximal cooling rate; P_{avg} average cooling rate throughout the 8-h measurement; T_c cooling duration when cooling power ≥ 20 W/m^2; *AUC* area under the curve, indicating cooling capacity; P_{avg}' average cooling rate during T_c'; P_{eff} effective cooling rate ($P_{avg}' - P_{base}$); P_{base}: baseline power input measured with cooling vests not activated; T_c' duration of cooling calculated until P_{eff} has decreased to 50W; *N.A.* not available

(Fig. 3). In addition, virtually no impact by the relative humidity was observed in the LCV, which differed from the ACV (Table 3).

In the case of EVAP, meaningful cooling performance could be only captured by [No_SWT], whereas the values could not be measured in [SWT_HD] and [SWT_HH] because sweating evaporation from the skin was maximally activated by the sweating thermal manikin (Fig. 3, Table 3). Therefore, the Hybrid also showed similar results in [SWT_HD] and [SWT_HH] because the evaporation of the cooling vest did not provide an additional cooling effect in the sweating thermal manikin (Fig. 3b, c). On the other hand, the Hybrid presented an improved cooling performance in the [No_SWT] compared to the PCM (Fig. 3a). In addition, PCM had a shorter cooling effect than EVAP (PCM: T_c 89 min, EVAP: T_c 283 min) in [No_SWT] (Table 3, Fig. 3a).

These results are also shown in Fig. 4, which describes P_{avg} and T_c for [No_SWT] (Fig. 4a) and P_{eff} and T_c' for [SWT_HD] and [SWT_HH].

Discussion

The present study examined the cooling performance of five types of commercially available cooling vests using three thermal manikin test scenarios adopted from Ciuha et al. (2021) and ASTM F2371-16. Another test protocol was modified from ASTM F2371-16 to simulate the typical hot and humid environmental conditions experienced in a South Korean summer.

As expected, the cooling performance differed significantly according to the test protocols. For example, the cooling effectiveness of the ACV built with fans was greatly underestimated using a non-sweating thermal manikin because its two main pathways of cooling (convection and evaporation) were restricted with a non-sweating thermal manikin under isothermal conditions. When considering the continuous

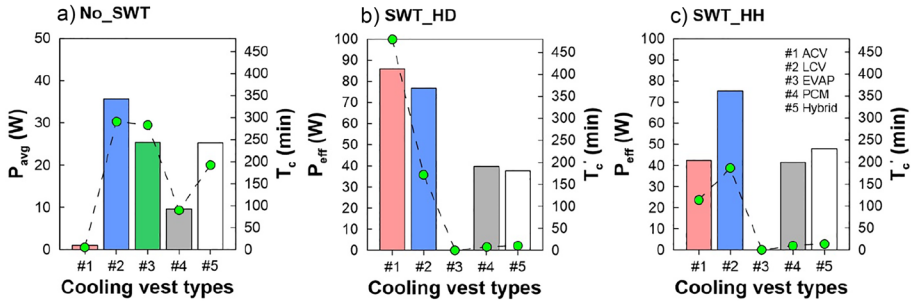

Fig. 4 Graphical comparison of representative cooling performance parameters; the average cooling rate (P_{avg}) of [No_SWT] condition (**a**) and effective cooling rate (P_{eff}) of two sweating conditions (**b**, **c**). In all figures, green dots indicate the cooling duration time measured during each protocol

perspiration of human skin, the excessively reduced cooling effectiveness of the ACV observed in the non-sweating manikin test suggests great incongruity between the current test results and the actual vest performance. In addition, sweating thermal manikin could not measure the evaporative cooling vest under either environmental condition. Its cooling performance was occupied by activated evaporation from the skin. In a sweating thermal manikin, however, where the skin was already saturated by water perfusion, the cooling vest would be another evaporative resistance rather than an evaporation accelerator.

The cooling effectiveness of the ACV showed the strongest dependence on the relative humidity among tested cooling vests. At 35 °C and 40%RH, P_{max} and P_{eff} were approximately 2.0 times greater than those measured at 35 °C and 70%RH. The cooling duration time (Tc') was more than 4.2 times longer in the hot–dry conditions than in the hot–humid conditions. This was a clear distinction compared to the other cooling vests, showing that P_{eff} was similar or slightly lower under the hot–humid conditions. These data confirm previous findings that ventilation clothing significantly increased the evaporative heat loss in hot environments (Lu et al., 2015). Yi et al. (2017) explored the cooling effectiveness of an ACV with built-in fans under hot and humid conditions. They concluded that the ventilation provided by embedded fans led to a notable improvement in evaporative heat loss compared to the fan-off conditions. In addition, Jay et al. (2015) reported that fan cooling was beneficial for removing heat at an air temperature of 36 °C and 33%RH and 40 °C and 27%RH, but limited cooling advantages were noted at 36 °C and 67%RH and 40 °C and 54%RH. Wang and Song (2017) compared four types of cooling vests (i.e., fan cooling, evaporative cooling, hybrid cooling combining fans and evaporative cooling, and liquid cooling) under three environmental conditions, including hot–humid and hot–dry conditions, based on an adaptive manikin method. In the study, ACV exerted cooling benefits at 36 °C and 33%RH, but the predicted hypothalamic and mean skin temperatures were much higher at 36 °C and 67%RH. The current and previous studies suggest that the effectiveness of an ACV would be limited under very hot and humid conditions, where the evaporation of sweat is restricted (e.g., under the encapsulated protective clothing after the microclimate is saturated with water vapor). Therefore, the performance of an ACV can be overestimated or underestimated significantly depending on the environmental temperature, which is not currently explained in

ASTM F2371-16 and needs to be stated to avoid misunderstood applications and incorrect decision-making in the industry.

Among cooling strategies, PCMs are regarded as practical and effective measures in improving the physiological and perceptual responses during heat stress among various cooling vests (Ciuha et al., 2023; Golbabaei et al., 2022; Yi et al., 2017). In general, the physiological advantages of PCMs were particularly prominent in hot and humid environments or when worn beneath protective clothing, where evaporative and convective heat loss may be impractical and restricted (Ciuha et al., 2023; Kenny et al., 2011; Maley et al., 2020). A recent physiological evaluation of various cooling vests under hot and humid conditions (35 ℃ and 50%RH) showed that cooling vests with PCM inserts effectively decreased the skin temperature of a torso with greater perceptual cooling effects. A review article by Golbabaei et al. (2022) explained that PCMs exhibited the most effective results in enhancing the physiological and perceptual cooling effects, surpassing the LCV and ECV. In the present study, however, the PCMs were not as effective as the LCV in all scenarios and the ACV when used by a sweating thermal manikin. Among the three test protocols, under non-sweating conditions, PCM showed a noticeable maximal cooling power at the initial phase, which is comparable to the LCV, but the cooling effect decreased drastically and did not last longer. When combined with the evaporative mode (Hybrid), the maximal cooling power and cooling duration were improved. By contrast, the additional advantages of evaporative cooling were barely detectable when tested with a sweating thermal manikin regardless of the relative humidity in the chamber. The specification of cooling vests tested may have contributed to this discrepancy. IH 15, an identical vest to the PCM in this study, showed relatively lower cooling performance among the various PCM vests (Ciuha et al. 2020). Because this study was planned to compare test methods rather than cooling vests, caution should be taken in that the measured outcomes of each vest do not represent each cooling mode.

Further discussion on the analytic parameters may involve addressing the subtle discrepancies between Ciuha et al. (2021) and ASTM F2371 when calculating parameters such as P_{avg} versus P_{avg}' and T_c versus T_c'. P_{avg} was determined by averaging the cooling rate over eight hours. While this approach facilitates a comparison of the overall cooling performance, it could not effectively elucidate the actual average performance during operation because P_{avg} can differ significantly depending on T_c, even when the actual cooling rate during T_c is identical. The approach of ASTM F2371 alleviates these concerns because Pavg' is calculated by averaging the cooling rate exclusively during Tc'. Another discrepancy lies in the definitions of T_c and T_c'. In ASTM F2371, T_c' is defined as the duration of cooling from initiating the cooling process. In contrast, Tc is measured from the point of the maximal cooling rate. In the current study, a distinctive peak was observed within the initial few minutes of each eight-hour measurement. While this method can be perplexing, particularly in cases where the cooling rate exhibits an increasing phase or multiple peaks, the definition of the cooling duration time in ASTM F2371 may provide greater clarity.

Thermal manikin test methods might be a convenient measure to evaluate the cooling power of personal cooling garments quantitatively, but it could lead to overestimations and underestimations of the cooling performance. First, as noted in previous studies (Wang & Song, 2017), the temperature gradient between the skin

and the cooling vest is exaggerated, especially in the mode of maintaining a constant skin temperature and measuring the regional power input, which can result in a decreased cooling duration with a limited cooling capacity in the manikin test. Using an adaptive thermal manikin might be a possible alternative way to reduce the difference from the actual human thermoregulatory response (Wang & Song, 2017). Second, human perspiration cannot be completely zero, contrasting with a non-sweating thermal manikin. Even when the human apparently does not sweat, insensible perspiration, also known as transepidermal water loss, constantly occurs. Moreover, continuously saturated sweat over the whole body is not possible, which would cause dehydration. Therefore, non-sweating and sweating manikins could not replicate the human body. On the other hand, the thermal manikin can postulate non-real but remarkably stabilized heat exchange conditions so that dry heat loss and evaporative heat loss from the cooling vest can be obtained under isothermal conditions. Modifying the environmental conditions and clothing layers for the thermal manikin test to be similar to the occupational settings would be somewhat helpful for increasing the similarity to the actual performance, but caution should be taken when interpreting the results. Finally, the thermal manikin test could not consider the physical burden imposed by the weight of the vests. The weight of LCV, the heaviest vest in this study, weighing 4.43 kg, would be an additional physical burden while increasing the metabolic rate, which was not considered in the current thermal manikin test protocols except for the adaptive thermal manikin model.

In addition, the measured outcomes can differ according to various factors. Clothing layers and ensembles would prominently influence the results. For example, cooling vests should be worn on the appropriate clothing layer. In this study, PCM vests were worn on shirts, commonly worn beneath the working uniform on the skin, to remove body heat effectively. Nevertheless, cooling vests were worn on the shirts to reflect the workers' opinions and preferences, which were investigated before this study. They reported that direct skin contact with PCM vests whose PCM had a melting temperature of 15 ℃ caused severe coldness and discomfort on the skin. In addition, cooling vests should be chosen carefully to be perfectly fitted on the manikin and worn according to the manufacturer's instructions. For example, in the case of the ACV, the fit and size of the vests can affect the air movement in the microclimate of clothing, yielding varied outcomes. Finally, the different configurations of thermal manikin should also be considered when analyzing inter-laboratory test results because the different surface areas of the manikin require different power inputs to maintain a stable temperature. Further inter-laboratory comparative tests could be conducted to verify the reproducibility of the testing methods of cooling vests using thermal manikins.

Nevertheless, this study is still noteworthy for highlighting that there is *no one-size-fits-all evaluation method for cooling vests* among tested protocols based on thorough comparisons among various commercially available cooling vests. Given the necessity for more widespread use of cooling vests in various workplaces to prevent heat-related illness and to improve workers' comfort and safety, accessible guidelines for an evaluation of cooling vests are needed to assist decision-makers.

Conclusions

This study examined the cooling performance of five commercially available cooling vests using three thermal manikin test scenarios: adaptations from Ciuha et al. (2021) and ASTM F2371-16 and a modified protocol simulating the hot and humid conditions in a South Korean summer. The results revealed substantial variations in cooling performance across different test protocols, emphasizing the importance of careful test method selection. In particular, certain cooling vests exhibited immeasurable performance in specific test methods, shedding light on the limitations of each testing scenario. For example, the effectiveness of air-cooled vests with fans and evaporative cooling vests could not be measured under non-sweating and sweating conditions, respectively. Contrary to expectations, PCM inserts, often regarded as effective in heat stress, demonstrated lower effectiveness than liquid-cooled and air-cooled vests in specific scenarios. On the other hand, emphasis should be placed on the significant differences in the performance evaluation according to the test method for each cooling type rather than on ranking the cooling vests because the individual performance would vary by the design and individual performance of the cooling components of the vest. The study also revealed limitations of thermal manikin tests, including exaggerated temperature gradients between the skin and vests and the inability to replicate human perspiration accurately. Despite these challenges, the study contributes to the field by emphasizing the lack of a one-size-fits-all evaluation method for cooling vests and the need for accessible guidelines to inform decision-makers focused on enhancing workplace safety and comfort.

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Authors' contributions
SK, SL, and DL developed and planned experimental design, and SK, SL, and SS conducted experiments and analyzed data. Each author was responsible for writing specific subsections, and for editing all parts of this work. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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