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Efficacy of cooling vests based on different heat-extraction concepts: The HEAT-SHIELD project

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A R T I C L E I N F O

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A B S T R A C T

Introduction: A wide range of cooling vests for heat-strain mitigation purposes during physical work are available on the market. The decision regarding the optimal cooling vest/concept for a specific environment can be challenging by relying solely on the information provided by the manufacturers. The aim of this study was to investigate how different types of cooling vests would manifest/perform in a simulated industrial setting, in a warm and moderately humid environment with low air velocity. Methods: Ten young males completed six experimental trials, including a control trial (no vest) and five trials with vests of different cooling concepts. Once entering the climatic chamber (ambient temperature: 35 °C, relative humidity: 50 %), participants remained seated for 30 min to induce passive heating, after which they donned a cooling vest and started a 2.5-h of walk at 4.5 km·h^{-1}. During the trial, torso skin temperature (T_{sk}), microclimate temperature (T_{micro}) and relative humidity (RH_{micro}), as well as core temperature (rectal and gastrointestinal; T_c) and heart rate (HR) were measured. Before and after the walk, participants conducted different cognitive tests and provided subjective ratings throughout the walk. Results: The use of the vests attenuated the increase in HR (103 ± 12 bpm) when compared to control trial (116 ± 17 bpm, $p < 0.05$). Four vests maintained a lower torso T_{sk} (31.7 ± 1.5 °C) compared to control trial (36.1 ± 0.5 °C, $p < 0.05$). Two vests using PCM inserts attenuated the increase in T_c between 0.2 and 0.5 °C in relation to control trial ($p < 0.05$). Cognitive performance remained unchanged between the trials. Physiological responses were also well reflected in subjective reports. Conclusion: Most vests could be considered as an adequate mitigation strategy for workers in industry under the conditions simulated in the present study.

1. Introduction

In many working real-life scenarios, which include moderate to high intensity work and/or exposure to environmental heat stress, air-conditioning of the work environment may not be feasible. Namely, the activities might be performed either outdoors or in large spaces, which would require an investment of a substantial amount of energy for cooling purposes (Borg et al., 2021; Ciuha et al., 2019; Gao et al., 2018; Jay and Brotherhood 2016). In such scenarios, personal cooling strategies can provide an efficient and affordable solution. The use of cooling vests has been studied extensively in occupational settings which require workers to wear protective clothing (Bach et al., 2019; Cadarette et al. 2006; de Korte et al., 2021; Foster et al., 2020; Maley et al., 2020; McLellan et al., 1999). It has been projected that increasing global temperatures will be accompanied by more frequent, longer and more severe heat waves (Pogačar et al., 2018), which are proven to affect human capacity for physical and cognitive tasks (Ciuha et al., 2019; Ioannou et al., 2021b; Piil et al., 2020; Shibasaki et al., 2017). The use of cooling vests for heat stress mitigation purposes has also been considered in other occupations (Chan et al. 2013, 2015, 2016; Ioannou et al., 2021a; Roelofsen and Jansen 2022; Yi et al., 2017a) and in sports settings (Luomala et al., 2012; Webster et al., 2005; Wegmann et al., 2012). A wide range of cooling vests are available on the market, using different cooling concepts: conduction, convection and evaporation, and a combination of these. The decision regarding the optimal cooling vest/-concept for a specific environment can be challenging, as the user can only rely on the information provided by the manufacturers. Apart from the vest's cooling capacity, its design and material also importantly impact the vest's usability (Chan et al., 2018; Ngô et al., 2020). Namely, once the cooling capacity of the vest is exhausted, the vest becomes an additional layer of insulation, hindering the sweat evaporation from the body (Ciuha et al., 2021). Specifically, sweat evaporation presents a major mechanism for dissipating heat. Evaporation is however compromised in high water-vapour pressure environments (Epstein and Sohar 1985; Tyler 2019) in which the vests promoting cooling by

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Abbreviations

COMP	CompCooler vest
HR	heart rate
HYB	Inuteq Bodycool Hybrid vest
RH_{micro}	torso microclimate relative humidity
STA	StaCool industrial vest
T_{gi}	gastrointestinal temperature
T_{micro}	torso microclimate temperature
T_{re}	rectal temperature
T_{sk}	skin temperature
VO_{2max}	maximal oxygen uptake
VRTX	Vortex vest
XTREM	Inuteq Bodycool Xtreme vest

conduction seem more appropriate (Yi et al., 2017b).

Recently, we evaluated the cooling capacity of various commercially available cooling vests (Ciuha et al., 2021). Following an extensive market survey, 80 different cooling vests were classified according to their cooling concepts. Of these, 23 were chosen for further evaluation. Their cooling capacity, thermal and evaporative resistance were determined with the Jozef Stefan Institute thermal manikin. In this study, a new experimental protocol was developed to determine the cooling capacity of cooling vests based on the average as well as maximal cooling power ($W{\cdot}m^{-2}$) and cooling duration (min). Whilst thermal manikins have many advanced and useful features that make them a relevant simulation of human body heat exchange, providing quick, accurate and repeatable results (Holmér 2004), they have certain limitations. For example, they cannot reflect typical human physiological responses to a change in thermal state, such as increased sweat secretion, vasoconstriction, and vasodilatation, and they do not provide feedback on the ergonomic aspects of the vest, including practicality and overall comfort, which have been reported as the crucial components by the users (Chan et al., 2015). Therefore, in this study, five vests of different cooling concepts which were found to provide the best combination of cooling power and duration when evaluated on a thermal manikin, were further evaluated on human participants. As part of the European Commission Horizon 2020 project HEAT-SHIELD, developing effective solutions to promote health, prevent disease, and maintain productivity of workers in European key industries, the main aim of the study was to observe how different cooling concepts would perform in a simulated industrial setting, with workers exposed to warm and moderately humid environment with low air velocity. We therefore tested the hypothesis that candidate cooling vests would mitigate heat strain, as reflected in some or all of the measured parameters, including physiological and perceptual responses, and cognitive performance.

2. Methods

2.1. Participants

The study was approved by the National Committee for Medical Ethics of the Republic of Slovenia (no. 0120-29/2020) and was conducted in accordance with the Declaration of Helsinki. The minimum required sample size for investigating potential differences among various cooling vests (six repeated trials) was calculated using the difference in T_{sk} between individuals working with (34.1 ± 0.8 °C) and without (33.1 ± 0.3 °C) cooling vests in the heat (Ioannou et al., 2021a). Using these data, an effect size (d) of 1.59 (f = 0.8) for the differences between the two scenarios was computed. Assuming an α of 0.05 and β of 0.99, a total sample size of five would provide enough power to detect a statistical difference of a similar magnitude (G*Power Version 3.1.9.2) (Faul et al., 2007). Based on these calculations, a total of ten healthy young males participated in the study (age: 22 ± 4 years, height: 184 ± 7 cm, weight: 81 ± 13 kg, maximal oxygen consumption: 54 ± 4 ml $kg^{-1}{\cdot}min^{-1}$).

2.2. Cooling vests

Previously (Ciuha et al., 2021), using a thermal manikin we evaluated the cooling efficiency of 23 different cooling vests. Based on their cooling concept, they were categorised as active air-cooling vests, active water-cooling vests, evaporative vests, vests using phase change materials, or hybrid vests. For the purpose of the study, a novel methodological approach was designed, with duration of the measurements tailored to the length of a standard 8-h workday, providing information on the cooling capacity of each vest by considering its cooling duration (min) and cooling power ($W{\cdot}m^{-2}$). From each of the five cooling concepts, one vest with the best cooling characteristics (details in Fig. 1) was further tested on participants, as documented in the present study and described below:

Active air-cooling vest: The vest was connected to a source of compressed air (6.9 bar). The vortex tube incorporated the Venturi effect, causing a decrease in temperature of the air (~19 °C), entering the microclimate at the posterior of the vest.

Active water-cooling vest: The vest provided cooling by pumping and circulating water between the imbedded tubes and a 2-L bladder, containing 1.5 L of ice and 0.3 L of ice-cold water.

Evaporative vest: The vest was soaked in 35 °C water for 1–2 min (stored inside the climatic chamber). Next, the excess water was squeezed out to avoid dripping from the fabric, followed by donning of the vest.

Vest using phase-change material (PCM) inserts: PCM inserts were placed in a freezer (−18 °C) for approximately 24 h. Directly before each experiment, frozen inserts were inserted in the designated pockets of the vest.

Hybrid vest: The vest was a combination of the evaporative vest and vest using PCM inserts, therefore following the identical preparation processes as described above.

2.3. Testing protocol

The study took place in midsummer, with participants at least partly heat acclimatised when entering the study (depending on the level of daily heat exposure prior to the study). Participants visited laboratory on 8 separate occasions at a consistent time of day and a minimum of two days apart. They were instructed to abstain from caffeine and alcohol consumption throughout the study and to consume at least 500 ml of water the night before and the same amount before arriving to the laboratory. Following two preliminary sessions, 6 main experimental trials were conducted in a randomised order, including one control trial, wearing casual clothing with shorts and short sleeved T-shirt, and 5 trials, each with a different cooling vest (Fig. 1) worn above the basic attire. During the two preliminary sessions, participants were familiarised with the experimental procedures, completed a health screen questionnaire, and provided written consent for participating in the study. During the two preliminary sessions, participants underwent body composition and maximal oxygen uptake (VO_{2max}) assessments. Body composition was assessed using dual-energy X-ray absorptiometry (DXA) using a fan-beam densitometer (Discovery W– QDR series, Hologic, Massachusetts, USA) and VO_{2max} using a metabolic cart (Quark CPET, Cosmed, Rome, Italy) to obtain breath-by-breath respiratory responses, respectively.

For the main measurement sessions, participants arrived at the laboratory approximately 1.5–2 h prior to the trial to adapt to the controlled laboratory conditions (ambient temperature: 25 °C, relative humidity: 50 %). During this period, they ingested a radio pill and provided a mid-stream urine sample, as well as conducted baseline cognitive performance tests and questionnaires regarding their thermal/

Cooling concept	Active vest (water)	Active vest (air)	Evaporative vest	Vest with phase-change material inserts	Hybrid vest
Name	CompCooler	Vortex cooling vest	Inuteq Bodycool Xtreme	StaCool industrial vest	Inuteq Bodycool Hybrid
Abbreviation	COMP	VRTX	XTREM	STA	HYB
Specifications	Circulating water temperature of ~1°C when donning the vest	Compressed air ventilation providing microclimate temperature of ~19°C	Saturated with water	Phase change material (PCM) inserts (no data on the melting temperature available)	Combination of the evaporative vest and vest with PCM inserts (melting point: 6.5°C
Image of the vest					
Image of the cooling agent/mechanism					

Fig. 1. Cooling vests used in the study. Detailed description of the vests is provided in Ciuha et al. (2021).

moisture perception and exertion (in this order). Once completing the tasks, they entered a changing room, where they inserted a rectal probe and changed in shorts. Thereafter, their weight and weight of the remaining clothing items was recorded. Before donning the remaining clothing, the rest of the sensors were attached. Once prepared, they entered the climatic chamber.

2.4. Measurements

To ensure that participants were euhydrated at the start of the experiment, a urine specific gravity was assessed (USG, PAL-S, Atago, Japan). Values below 1.020 were considered as euhydration (Casa et al., 2000; Sawka et al., 2007). Participants were not provided with any additional fluids for the remaining of the trial so that any potential benefits in cognitive performance and subjective perceptions could primarily be attributed to the effects of the cooling. During the experiment, their torso skin temperature (T_{sk}, °C; Thermochron High, DS1921H–F5#, Berkshire, UK), torso microclimate temperature (T_{micro}, °C) and relative humidity (RH_{micro}, %; Modular Signal Recorder, MSR145WD, Seuzach, Switzerland), heart rate (HR, bpm; Suunto AMBIT3 RUN, Vantaa, Finland), rectal temperature (T_{re}, °C; Modular Signal Recorder, MSR145WD, Seuzach, Switzerland) and gastrointestinal temperature with a radio pill (T_{gi}, °C; BodyCap, eCelsius performance, Caen, France) were measured at 1-min intervals. The mean unweighted torso skin temperature was derived from four sites, with two sensors attached on the front torso (chest and abdomen) and two on the back torso (upper and lower back). Same locations were used for the microclimate temperature and relative humidity measurements, with sensors attached on the T-shirt, secured by safety pins. Before and after each trial, the participants (naked weight) and individual clothing items were weighted (Libela Elsi, Celje, Slovenia) and recorded for analysis. The trials were performed in a climatic chamber at the Jozef Stefan Institute laboratory, maintaining the ambient temperature at 35 °C and relative humidity at 50 %. After entering the chamber, participants were seated for 30 min to induce passive heating. During this time, they repeated the cognitive performance tests, evaluating reaction time and number of errors made. Then, the participants donned a cooling vest (Fig. 1) and started a 2.5-h walk on a treadmill at a speed of 4.5 km·h^{-1} with the treadmill set at an incline of 1 %. Every 30 min during the walk, participants reported subjective ratings of thermal, ergonomic, and wetness perception on the torso and overall exertion (Borg 6–20 scale; Borg 1970). Thermal and ergonomic comfort scale included ratings of 0: comfortable, 1: slightly uncomfortable, 2: uncomfortable, 3: very uncomfortable. Thermal sensation scale was derived from the ratings of −3: cold, −2: cool, −1: slightly cool, 0: neutral, 1: slightly warm, 2: warm, 3: hot (ANSI/ASHRAE 2013). Wetness perception included the ratings of 0: dry, 1: slightly damp, 2: damp, 3: very damp, 4: wet. After the walk, the vest was removed, and the same cognitive performance tests were administered to observe any heat stress related decrements in cognitive function. Upon completion of the final trial, participants were debriefed regarding their experience with each vest.

2.5. Assessment of cognitive performance

Three well-known cognitive performance tests were used in the study (Ioannou et al., 2021c), which have been developed as a free public-access computer software (www.famelab.gr/research/downloads/). Participants were familiarised with the tests during the two pre-experimental days. When completing the tests during the trials, participants were isolated from external visual and/or acoustic stimuli. All tests were administered on a tablet computer, with the screen brightness, sound volume and the test sequence remaining constant throughout the study. During each trial, the tests were conducted at three time points: at baseline (~40 min before entering the chamber), before the walk, and after the walk, requiring ~20 min for completion each time. Individual tests are described below:

Vigilance test: The task involved two squares vertically arranged. The pattern typically jumped from one square to the other. When the pattern repeated in the same square, however, participants were instructed to touch the screen as fast as possible. The total test duration was set to 6 min.

Memory test: A sequence of one to six digits (ranging from 0 to 9) in white font was displayed for 1.2 s each. Following a 2-s delay, a random digit (from the numbers that were previously presented) was presented in yellow font. Participants were required to indicate whether the yellow digit was part of the sequence of numbers presented or not by pressing the “yes” or “no” buttons on the screen as fast as possible. Each test included a total of 24 sequences of numbers.

Reaction time: Participants were requested to place a digit finger on the screen and to remove it as fast as possible after receiving a visual (i.e., screen turning from black to yellow) or acoustic (i.e., a loud beep) stimulus. The test was repeated three times for each – visual and acoustic stimulus.

2.6. Statistical analysis

Statistical analysis was performed using Statistica 12.0 (StatSoft, Inc., Tulsa, USA). Physiological data are reported as means ± standard deviation (SD), whereas subjective and cognitive performance data are presented as medians (range). Two-way repeated measures ANOVA (trial x time) was used to compare T_{re}, T_{gi}, T_{sk}, T_{micro}, RH_{micro} and HR. The study assessed the core temperature by using two different measurements – gastrointestinal temperature and rectal temperature. To our knowledge, no study to date has assessed this in combination with work/exercise performed in a hot ambient while wearing a cooling vest. The comparison of core temperature measurements obtained with a radio pill and rectal thermometer was conducted as a prelude to future field studies, which will only use radio pills; enabling estimates of T_{re}

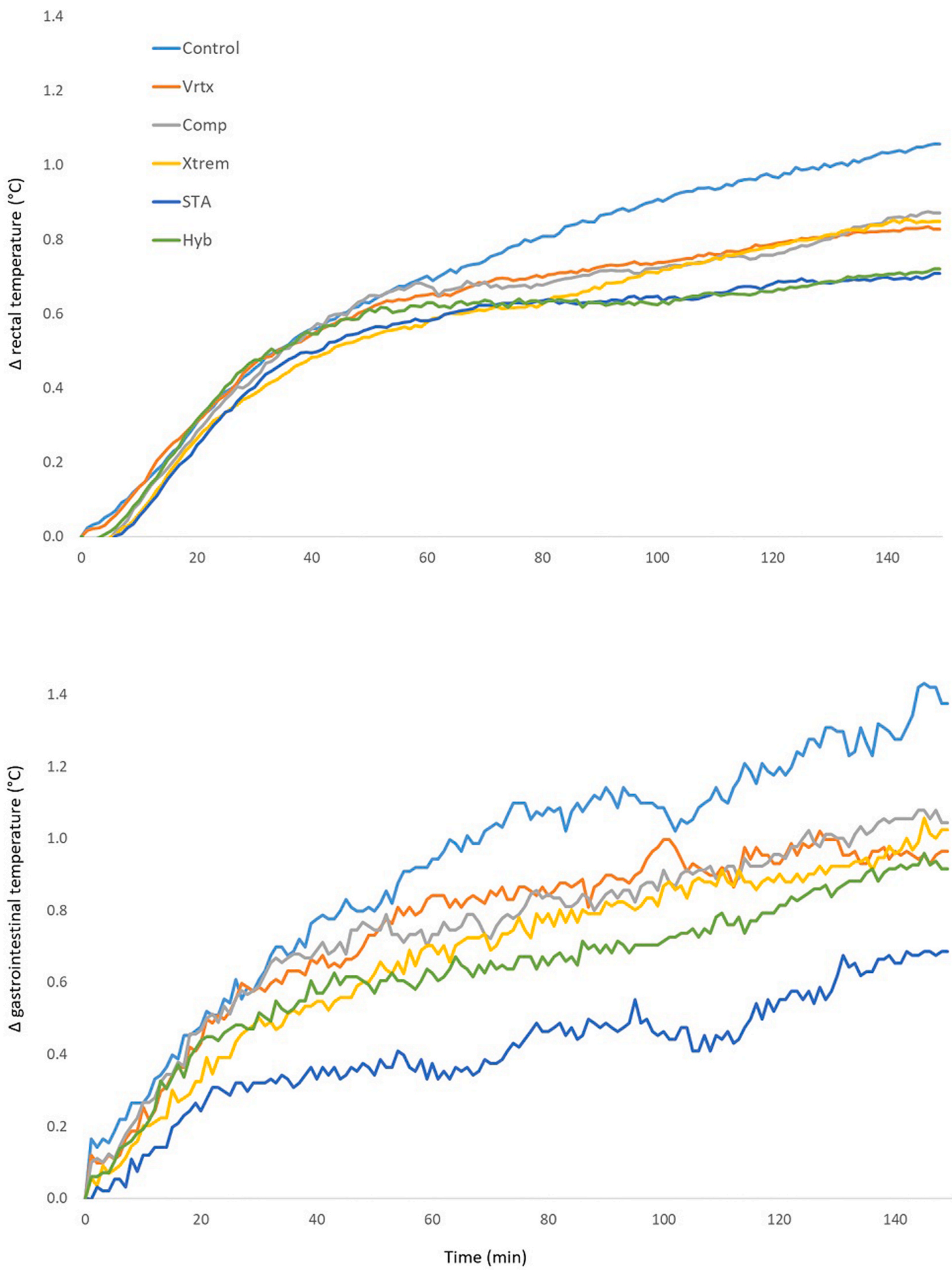

Fig. 2. Changes in core temperature (measured with a rectal thermometer and gastrointestinal pill) as the difference between the 30-min passive heating in a seated position and 150-min walking while wearing different cooling vests. Control: condition without the cooling vest; Vrtx: air-cooling vest; Comp: liquid-cooling vest; Xtrem: evaporative vest; STA: vests with PCM inserts; Hyb: hybrid as a combination of evaporative vest and vest using PCM inserts.

response from T_{gi} measurements. Comparison between the two measurements was conducted using a two-way repeated measures MANOVA (measurement x trial). A Tukey post-hoc test was employed to identify specific differences when main effects were observed. Due to non-normally distributed data, differences in subjective perceptions and cognitive performance were evaluated with a Wilcoxon matched pairs non-parametric test (Bonferroni correction). The alpha level of significance was set a priori at 0.05 (or 0.01 after Bonferroni adjustment).

3. Results

3.1. Core and skin temperature measurements

All trials were initiated at a similar core and skin temperatures ($p > 0.05$). An increase in T_{re} and T_{gi} (Fig. 2) was greater in control trial (T_{re}: 38.3 ± 0.4 °C, T_{gi}: 38.2 ± 0.04 °C, $p < 0.05$), when compared to trials with STA (T_{re}: 37.9 ± 0.2 °C, T_{gi}: 37.6 ± 0.5 °C) and Hyb vest (T_{re}: 37.9 ± 0.2 °C, T_{gi}: 37.9 ± 0.3 °C). STA vest maintained a lower T_{gi} also when compared to the remaining vests ($p < 0.01$), with the exception of Hyb vest ($p > 0.05$). Overall, the correlation between the two core temperatures was strong in all the trials ($r \geq 0.95$, $p < 0.001$).

When compared to the control trial (Fig. 3) all vests provided some level of cooling to the torso ($p < 0.001$), except the XTREM vest ($p > 0.05$). Significantly greater cooling compared to all other vests tested was provided by the vest using PCM inserts (STA), reducing the torso T_{sk} to 28.2 ± 3.0 °C during the walk ($p < 0.001$). COMP vest provided better cooling (32.4 ± 0.9 °C) when compared to XTREM vest (34.8 ± 0.4 °C, $p < 0.01$). The mean torso T_{sk} remained similar in the trials with VRTX (33.0 ± 1.4 °C) and HYB vest (33.1 ± 0.6 °C).

3.2. Microclimate temperature and relative humidity measurements

As observed from the T_{sk}, torso T_{micro} (Fig. 4) was also significantly lower while wearing STA vest (24.8 ± 2.1 °C, $p < 0.001$) when compared to the remaining vests (VRTX: 28.9 ± 1.8 °C; COMP: 30.8 ± 1.0 °C; XTREM: 33.3 ± 0.5 °C; HYB: 31.2 ± 0.7 °C). Conversely, it was significantly higher while wearing XTREM vest compared to remaining vests ($p < 0.05$). VRTX vest reduced the torso T_{micro} significantly when compared to COMP, XTREM and HYB vest ($p < 0.05$). Wearing the COMP and HYB vests resulted in similar mean torso T_{micro} (30.8 ± 1.0 °C and 31.2 ± 0.7 °C, respectively). As seen from Fig. 4, most vests increased the torso RH_{micro} (COMP: 84 ± 8%; XTREM: 96 ± 1%; STA: 85 ± 7%; HYB: 95 ± 2%), whereas the VRTX vest maintained a significantly lower RH_{micro} (41 ± 10%, $p < 0.001$). Torso RH_{micro} in the XTREM and HYB, the two water-saturated vests, was significantly higher ($p < 0.05$) compared to other vests. COMP and STA vests resulted in similar mean torso RH_{micro} (84 ± 8% and 85 ± 7%, respectively).

3.3. Heart rate

All trials were initiated at similar HR ($p > 0.05$; Fig. 5). HR increased progressively during the walk and was significantly higher during the control trial (116 ± 17 bpm, $p < 0.05$) when compared to remaining trials including cooling vests (VRTX: 103 ± 13 bpm; COMP: 105 ± 11 bpm; XTREM: 102 ± 13 bpm; STA: 100 ± 12 bpm; HYB: 105 ± 11 bpm).

3.4. Sweat secretion and evaporation

There was no significant difference in participants' weight loss, whereas the moisture retention in the clothing differed significantly between the trials (Table 1). Vrtx vest was the most effective in promoting evaporation, evident when compared to all the remaining vests ($p < 0.01$). Evaporation was also better in control trial when compared to trials with COMP, XTREM and HYB vest. XTREM and HYB evaporative vests retained more water in the clothing when compared to the STA vest ($p < 0.01$).

3.5. Cognitive performance tests

No between-trial differences in the obtained scores of any cognitive tests were observed. For the reaction time and vigilance test, the scores also remained similar during the trial (during baseline, pre-walk, and post-walk). However, during the memory test, the responses were faster after the walk with COMP (by 10 %) and XTREM vest (by 8 %), when

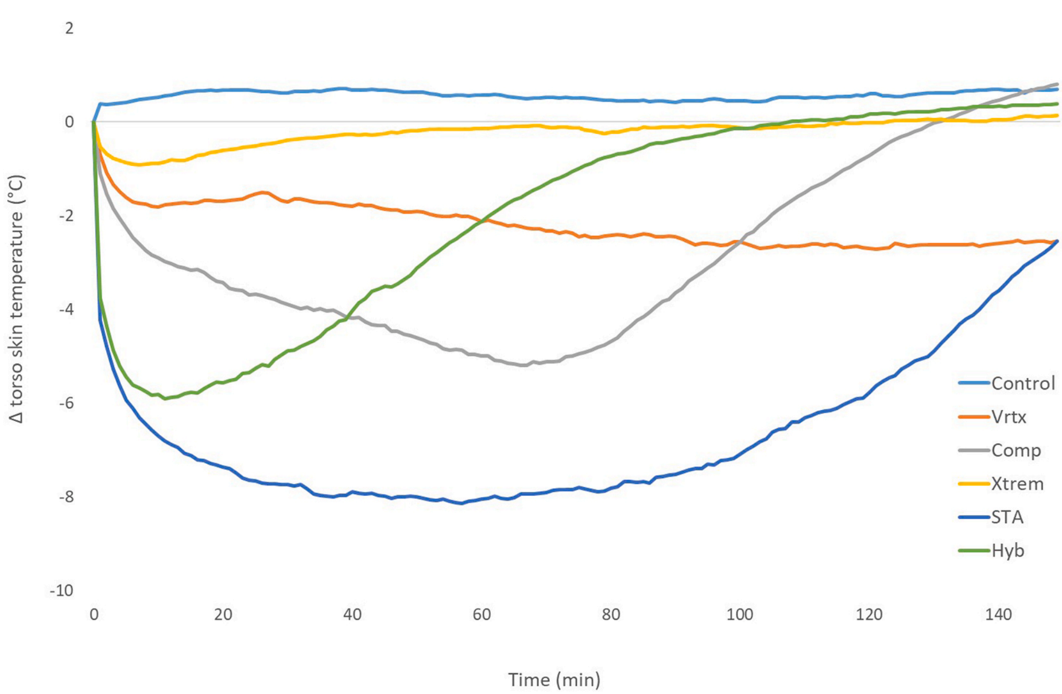

Fig. 3. Change in torso skin temperature as the difference between the 30-min passive heating in a seated position and 150-min walking while wearing different cooling vests. Control: condition without the cooling vest; Vrtx: air-cooling vest; Comp: liquid-cooling vest; Xtrem: evaporative vest; STA: vests with PCM inserts; Hyb: hybrid as a combination of evaporative vest and vest using PCM inserts.

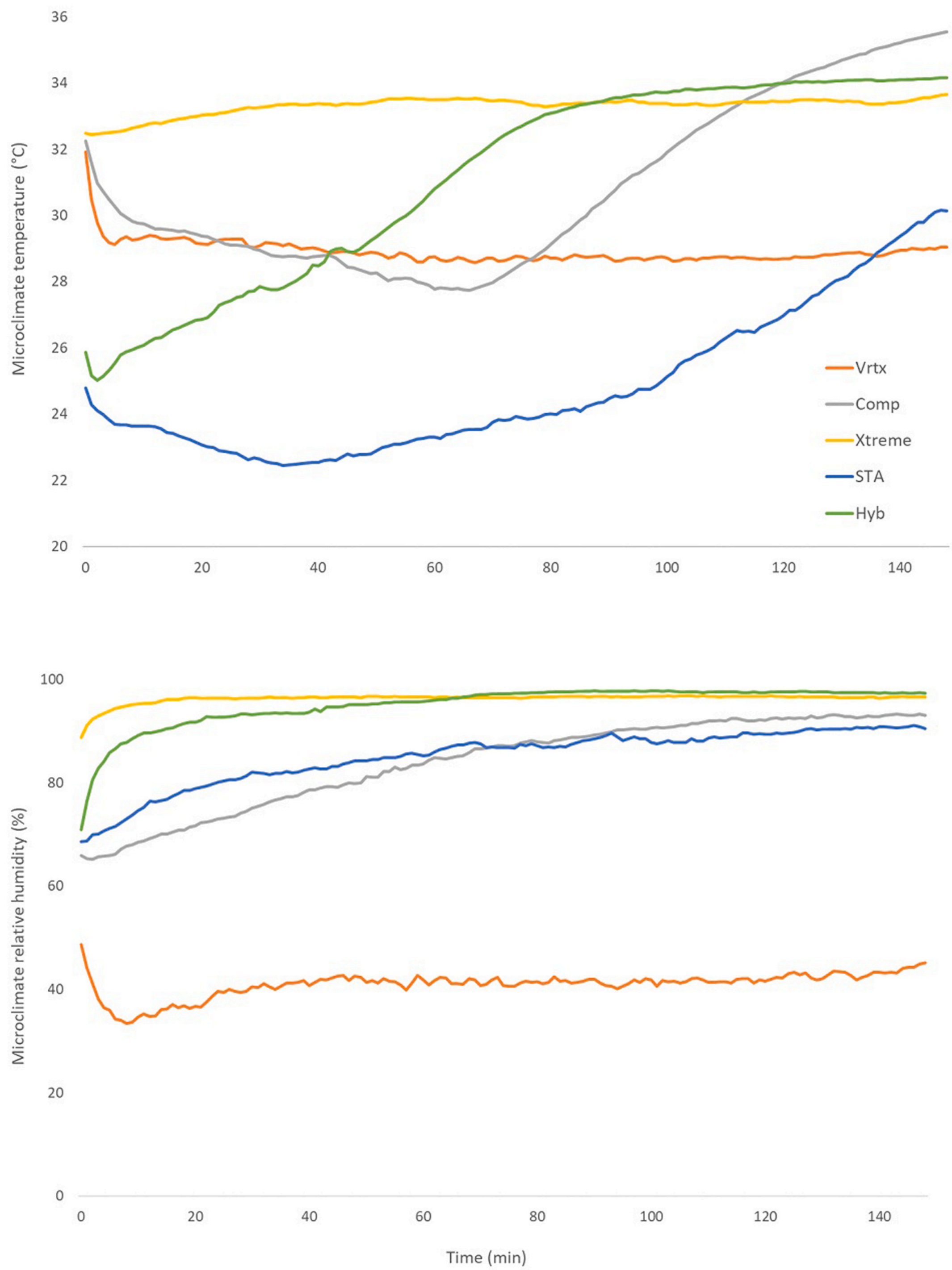

Fig. 4. Torso microclimate temperature and relative humidity during 150-min walk (the vests were donned on after 30 min of passive heating in a seated position). Vrtx: air-cooling vest; Comp: liquid-cooling vest; Xtrem: evaporative vest; STA: vests with PCM inserts; Hyb: hybrid as a combination of evaporative vest and vest using PCM inserts.

compared to responses recorded during baseline with no vest ($p < 0.01$).

3.6. Subjective perceptions and reports

Baseline ratings were similar between the trials. The torso region covered by different vests did not affect the overall body perception throughout the trial. Overall, the STA vest was rated as cooler and dryer on the skin and therefore more thermally comfortable, when compared to the XTREM and HYB vests ($p < 0.01$). VRTX vest was also perceived as cooler when compared to the XTREM vest ($p = 0.007$). Rating of perceived exertion was similar between the trials.

After completing all the trials, participants reported overall subjective evaluation of the five vests. In general, most participants (8/10) assessed the STA vest as optimal in terms of their perception of cooling. COMP and HYB were also reported to provide good cooling, however only short term (~1 h). XTREM vest was reported to be light and nicely designed but provided minimal cooling effect, with the feeling of wetness perceived as uncomfortable. Conversely, whilst the VRTX vest was reported to provide sufficient cooling throughout the trial, it was considered as poorly designed (too loose), and loud due to the inherent

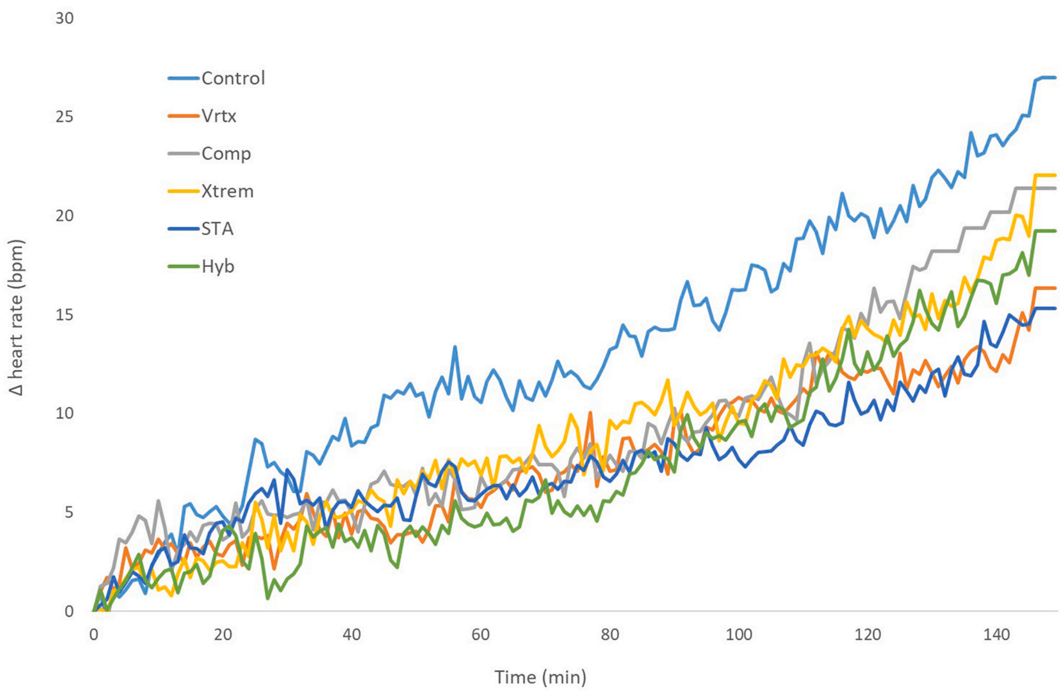

Fig. 5. Change in heart rate as the difference between the 30-min passive heating in a seated position and 150-min walking while wearing different cooling vests. Control: condition without the cooling vest; Vrtx: air-cooling vest; Comp: liquid-cooling vest; Xtrem: evaporative vest; STA: vests with PCM inserts; Hyb: hybrid as a combination of evaporative vest and vest using PCM inserts.

Table 1
Participants' weight loss and moisture retention in the clothing during the trials.

	Participants weight loss (kg)	Clothing moisture retention (g)
Control	1.2 (1.0–1.8)	31 (6–303)
Vrtx	1.2 (0.9–1.8)	23 (8–154)
Comp	1.2 (0.8–1.8)	80 (31–359)
Xtrem	1.2 (0.9–2.1)	109 (41–368)
STA	1.1 (0.8–1.6)	67 (29–265)
Hyb	1.1 (0.7–1.7)	128 (57–361)

Note: Values are median (range).

noise generated by the source of compressed air.

4. Discussion

The present study aimed to investigate the performance of different cooling concepts in a simulated industrial setting, with participants exposed to warm and moderately humid environment with low air velocity. Under the studied environmental conditions (ambient temperature: 35 °C, relative humidity: 50 %), the vests provided different levels and durations of cooling. Apart from the XTREM vest, all vests significantly attenuated the increase in torso T_{sk} and/or T_{re} and T_{gi} when compared to the control condition (no cooling vest). Physiological responses, including core and skin temperatures, as well as microclimate temperature and relative humidity, were also reflected in subjective reports, with participants identifying clear differences in subjective ratings of perception during different trials. Therefore, the majority of the tested cooling vests could be considered as providing an adequate heat-stress mitigation strategy for industry workers. However, it should be noted that the outcomes of the study are a function of the administered ambient conditions.

4.1. Physiological responses

As expected, the VRTX vest, connected to an unlimited source of compressed air cooled by a vortex system, provided constant and stable cooling throughout the trial (torso T_{sk}: ~33.0 °C). The strongest cooling, however, was provided by STA vest, using frozen PCM inserts, which reduced the torso T_{sk} to ~27 °C, attaining the same temperature as the VRTX towards the end of the walk. COMP and HYB vests also substantially reduced torso T_{sk} (the lowest measured torso T_{sk} were 29 and 30 °C, respectively), but their cooling power began to decrease after the first half of the 2.5-h walk, reaching similar levels as in the control trial by the end of the walk. XTREM vest reduced torso T_{sk} by only ~1 °C when compared to the control trial. Similar responses were also noted in the T_{micro}, measured between the t-shirt and the vest. VRTX vest maintained the RH_{micro} at 40 %, whereas the remaining vests reached levels between 90 and 97% after approximately 1 h of walking, persisting until the end of the walk. High RH_{micro} in the XTREM and HYB vest was primarily attributed to soaking the two vests in water before donning, whereas for the STA and COMP vest it was most likely produced by condensation as a result of an interaction between the warm body and the cooling agent. Thereafter, when the cooling capacity was exhausted, it was most likely the result of accumulated sweat which could not evaporate due to impermeable materials used in the vests.

In the present study, air temperature was maintained at 35 °C, relative humidity at 50 %, wind speed at 0.3 m·s^{-1}, and solar radiation at 0 W·m^{-2}. The overall heat stress experience by our participants was 28.8 °C Wet-Bulb Globe Temperature (Ioannou et al., 2022). Such environmental conditions were chosen to avoid favouring any particular vest. For example, vests using PCM inserts are particularly beneficial in hot and humid environments and/or when worn underneath protective clothing, where evaporative and convective heat loss are not feasible or restricted (Kenny et al., 2011; Maley et al., 2020). A recent systemic review of studies evaluating various cooling vests revealed that PCMs seem the most effective in improving physiological and perceptual responses (Golbabaei et al., 2020), which was also supported in the present study. On the other hand, evaporative vests can be particularly efficient in dry conditions, accompanied by greater air velocity, however, these are also conditions that reduce their cooling capacities by substantially augmenting water evaporation (Rykaczewski 2020). The cooling capacity can be further enhanced by certain hybrid combinations (Lu et al., 2015; Wang and Song, 2017) or mixed-method cooling (Yanaoka et al., 2022).

Previous studies, evaluating the benefits of cooling vests on participants, have measured core temperature at various sites, including oral (Ashtekar et al., 2019; Zare et al., 2019), tympanic (Itani et al., 2018; Karkalić et al., 2015), rectal (Butts et al., 2017; Chaen et al., 2019), gastrointestinal (Barr et al., 2009; Guo et al., 2019; Song and Wang 2016) and oesophageal temperature (Arngrïmsson et al., 2004; Kenny et al., 2011). Most likely, the optimal site would be oesophageal temperature measured at the level of the myocardium, since all the vests cover the thoracic region. The present study determined the core temperature from two sites, including T_{re} and T_{gi}, to identify any potential differences. As field studies have typically used ingestible radio pills (Ioannou et al. 2021a, 2021c), the ability to estimate T_{re} from T_{gi} seems important. In the present study, T_{re} and T_{gi} displayed similar outcomes with lower increase in core temperature measured while wearing the two vests using PCM inserts (STA, Hyb) in relation to control trial. Similarly, this was observed in the study by Arngrïmsson et al. (2004), which assessed the benefits of the vest using PCM inserts as a precooling strategy before a 5-km run, with both rectal and oesophageal temperature displaying significant difference between the trial with the cooling vest and control trial.

4.2. Cognitive performance

The present study observed no changes in mental performance tasks between the trials. Conversely, Tang et al. (2021) observed improved performance in all the tasks when providing cooling to the torso in relation to control trial with no cooling. Their study was however performed in a seated position for only 1 h with a 30-min block of performing different tasks, whereas our study included 2.5 h of walking and three 20-min blocks with different tasks (at baseline, pre-walk, post-walk). Most likely, different mental performance outcomes between the two studies could be attributed to the longer experimental protocol used in our study, which reduced the cooling capacity of the vests by the time the trial was completed, evident in increasing T_{sk} as well as subjective thermal sensation reports. Since the mental performance tests were conducted before and after the walk, and not in-between, any potential differences between the control trial and the trials with cooling vests might have been diminished by the end of the walk.

Interestingly, our study observed some differences in performance between the stages of the trial, specifically improved reaction time after the walk when compared to baseline scores. This was observed for the memory test in trials with COMP and XTREM vest ($p = 0.009$). While wearing these two vests, the torso T_{sk} increased to a similar level as in control by the end of the walk, with participants feeling hot and uncomfortable at this point. The plausible explanation for this outcome could be found in change of mental alertness. Tham and Willem (2010) observed that exposure to cool environment reduced skin temperature and the sensation of skin temperature, and increased thermal discomfort and activation of sympathetic nervous system, which resulted in higher mental arousal. Although the present study was conducted in a hot environment, the mechanisms behind it could be similar – namely, an increase in thermal sensation and skin temperature decreased thermal comfort, which activated sympathetic nervous system and increased mental alertness, evident in improved memory test score.

4.3. Ergonomic aspect

Many studies have demonstrated that cooling vests improve physiological responses when performing industrial tasks (Ashtekar et al., 2019; Karkalić et al., 2015; Zhao et al., 2018). However, it has been shown that perceptual responses are just as important, with practicality and overall comfort being the crucial components (Chan et al., 2015). In the present study, one of the vests using frozen PCM inserts (STA) was reported to be cooler and more durable compared to the other vests. Interestingly, whilst some participants reported uncomfortable cold at the start of the experiment, others appreciated this characteristic. Nonetheless, vests using frozen PCMs should be optimised to prevent any cold injury (Zare et al., 2019). Furthermore, while the evaporative vest (XTREM) was considered as very comfortable to wear by many participants, it did not provide sufficient cooling – this was evident from physiological as well as subjective outcome measures. As the ambient conditions did not include high air velocity or/and low RH, the evaporative rate was relatively slow. On the other hand, it has been reported that fast evaporation does little to cool a person (Rykaczewski 2020). Additionally, participants also disliked the wet sensation of the two vests (XTREME, HYB), which were saturated with water. Finally, whilst the VRTX vest provided constant and reasonable cooling throughout the trial, participants complained about the lack of fitting as well as the noise, produced by a vortex system. These results clearly demonstrate that functionality of the vest should be accompanied by the comfort.

4.4. Considerations and limitations

Under the tested conditions, the vests in general provided shorter cooling duration than specified by the manufacturers. In fact, if used in an occupational setting, most tested vests (excluding the VRTX vest, connected to unlimited source of power) would need to be reactivated. Whilst evaporative vests could be reactivated easily by saturating them with water (XTREM), for some of the vests this would require certain level of logistical planning, such as freezing the inserts or preparing the ice (COMP, STA and HYB). Therefore, when selecting the optimal cooling vest for a specific working environment, the decision should be based on multiple factors, including practicality, efficiency, comfort, and affordability.

In the present study, participants entered the climatic chamber approximately 1.5–2 h after arriving and ingesting a radio pill. Although some studies suggest a longer ingestion period (Mündel et al., 2016; Wilkinson et al., 2008), we considered ~2 h as an adequate period for the pill to enter the intestinal tract, particularly since the primary aim of the study was to observe the relative differences in the obtained measurements between different vests in relation to control condition with no vest. Moreover, the study by Domitrovich et al. (2010) demonstrates that ingesting a pill 24-h or 40-min before the exercise in the cold provided similar measured core temperatures. This homogeneity along the internal intestinal tract was later confirmed in the study by Beaufils et al. (2018). Additionally, a more recent study by Notley et al. (2021) showed that time following ingestion does not influence the validity of telemetry pill measurements of core temperature during exercise-heat stress. These findings suggest that ingestion time of the radio pill (~2 h before the trial in the case of the present study) should not be a concern when interpreting the core temperature data, particularly when no food or beverages are being consumed. However, consuming food or liquid can affect the sensor temperature up to 8 h after the ingestion (Wilkinson et al., 2008) and therefore, in such case, a longer ingestion time is suggested.

This study tested the vests' cooling efficacy in only one environmental condition, which limits extrapolation of the results to other conditions. Future studies should assess the vests in various ambient conditions, to determine the temperature and relative humidity boundaries within which each vest performs optimally. Additionally, different populations should be studied. Finally, as proposed by Golbabaei et al. (2020), the experimental procedure should be standardised, allowing more reliable and valid comparison between different studies.

4.5. Conclusion

Under the studied conditions, the majority of the vests provided a certain level of physiological and perceptual relief and could therefore be considered as an adequate mitigation strategy for workers in industrial settings.

CRediT author statement

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Declaration of competing interest

There are no conflicts of interest.

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