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Meta-analysis study on the effects of personal cooling strategies in reducing human heat stress: Possible application to medical workers

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ABSTRACT

This study aims to evaluate the effectiveness of personal cooling strategies (PCSs) in reducing human heat stress, and determine the appropriate cooling strategies for medical workers. A meta-analysis method is employed to summarize, analyze and compare the effects of various PCSs on human physiological and psychological responses as well as performance, and to provide solid suggestions for selecting the optimal PCS for medical workers. External body cooling strategies (EBCSs) are found to exert large benefits in improving human physiological and psychological responses as well as human performance, and is more effective than internal body cooling strategies (IBCSs). IBCSs showed moderate effect in reducing core temperature, which may be practical for medical workers in extremely high outdoor temperatures and could be applied before wearing PPE. Liquid cooling clothing (LCC) provides larger cooling benefits than other types of EBCSs, then followed by air-cooling clothing (ACC) and hybrid cooling clothing (HCC), and phase change cooling clothing (PCMC) and semiconductor cooling device (SCD) ranks the last. Considering their applications for medical workers, nonportable LCC and ACC with cooling devices placed aside are practical for medical workers working in indoors or around buildings with less body movement and fewer postures; whereas portable LCC using a backpack and ACC using air fans are suitable for most medical workers with large range movements working in various locations. When using ACC, an air filtration system should be used together to filter the ambient air. SCD in the form of cooling chairs is only applicable for sedentary medical work around buildings in high outdoor temperatures. PCMC is more preferable for medical workers who work for a relatively short time or could change the PCM packs during work. This review serves as a foundational reference source for the selection or construction of highly effective and practical PCSs to reduce heat stress of medical workers.

Nomenclature

PCS	Personal cooling strategy
CON	No cooling condition

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EBCS	External body cooling system
IBCS	Internal body cooling system
LCC	Liquid cooling clothing
ACC	Air cooling clothing
PCMC	Phase change cooling clothing
HCC	Hybrid cooling clothing
SCD	Semiconductor cooling device
PCM	Phase change material
EFS	Effect size
RPE	Rating of perceived exertion

1. Introduction

To reduce the possible risk of infection, medical workers working on the frontline needs to wear medical protective clothing (PPE) to combat the COVID-19 pandemic [1,2]. The fabrics of the PPE are generally made of tight nonwoven fabric or woven fabric laminated with film [3], which are impermeable, and easily hinder the convective and evaporative heat dissipation from human body to the ambient [4], inducing body heat accumulation. Heat stress occurs when the accumulated heat inside the body outpaces its ability to dissipate, leading to body temperature rise, heat rate increase, profuse sweating, syncope and even heat stroke [5]. It is consistently discovered that medical workers wearing PPE easily suffer from heat stress after long working hours, especially in outdoors. Besides, the increasing ambient temperatures could also aggravate body heat stress because of the restricted heat conduction from human body to the ambient and even radiative heat gain from the ambient [6]. Researchers have consistently discovered that medical workers suffered from severe heat stress working in hot climates such as Guangzhou, India, Singapore and Italy, etc. [7,8,9]. However, it is often infeasible to reduce heat stress of medical workers using air-conditioners outdoors. In fact, air fans with high air velocity are frequently used, however it has limited effect because of the impermeability of the PPE [10]. For medical workers working indoors with air conditioning control, they still experience heat stress within an hour working at ambient temperature of 24 °C [4]. It is thus of a tremendous need to develop cooling strategies for medical workers to combat body heat stress.

Currently, various personal cooling strategies (PCSs) were developed aiming to reduce individual heat stress. The cooling medium in PCSs can promote human heat dissipation through convection, conduction, evaporation or the combined the heat transfer ways within a comfortable range [11]. In addition, the cooling medium can also absorb some heat from the ambient, reducing the heat transfer towards human body [11]. The cooling effects of PCSs can be evaluated using thermal manikin or human trials [12], and large cooling power or significant improved thermophysiological (such as core temperature and heat rate) and psychological responses (such as thermal sensation) was extensively detected [11,12]. In addition, applying PCSs could also weaken the influence of heat stress on human performance [13]. Human performance refers to the complete of a certain task, and can be measured using parameters such as physical performance (e.g., exercise duration, speed) or cognitive performance (e.g., accuracy, reaction time) [14,15]. The improvement on human performance is not only helpful for promoting people's productivity, but is also beneficial for enhancing their health and safety [13].

Presently, the PCSs include chairs and tables incorporating with cooling or heating elements [16], liquid cooling garments utilizing the embedded cooling tubes [17,18], phase change cooling garments using the latent heat of phase change materials [19], ventilated cooling garments with air fans [20], cold water immersion [21], intake of cooling drinks or ice [22], and hybrid cooling strategies that combine two or more of the above technologies [23]. The cooling strategies were extensively explored for their effectiveness in reducing body heat stress of construction workers, firefighters, and athletes in high ambient temperatures [23,25] or improving thermal comfort of office workers for saving indoor energy consumption [24]. Besides, many review studies were conducted to examine the effectiveness of the various PCSs in reducing heat stress of the above groups. For example, Chan et al. [13] reviewed the cooling performance of various personal cooling garments and examined their potential applications to occupational workers. Ruddock et al. [26] discussed the influence of practical cooling strategies involving garments, water immersion and cooling beverages on continuous exercise in the heat. Li et al. [27] performed a review study on the effectiveness of cooling clothing in reducing heat stress of firefighters. Song et al. [28] carried out a review to examine the effectiveness of various PCSs such as cooling/heating clothing, air fans and furniture in improving body thermal comfort under both warm and cold conditions. However, only few studies were retrieved for discussing the effects of PCSs on reducing heat stress of medical workers. Korte et al. [29] found the phase change clothing was effective in reducing heat stress of nurses wearing PPE in a moderate thermal environment, but its effect in high thermal temperatures was unknown. Lou et al. [30] investigated the effect of a lightweight wearable cooling and dehumidifying system (using an air ventilating vest and a moisture remover) for cooling human body by a thermal manikin, and detected it could provide about 3.2–5.0 times mean cooling power per unit weight compared to an air vest or a moisture remover in a prolonged working condition; whereas, its actual cooling effect as well as the resulting ergonomic issues were required to examine using human trials. Based on the limited number and limitations of studies, the appropriate PCSs for medical workers remains unclear.

In this study, a meta-analysis review study was performed to identify the reasonable cooling strategies for reducing body heat stress of medical workers. Different from the systematical review which could only describe the cooling effects of PCSs qualitatively, a meta-analysis review provides a quantitative method. It serves as an effective statistical method to find the precise overall effect of the intervention measures by integrating, quantifying, comparing, and analyzing all the published studies. Currently, several meta-analysis studies were found to examine the effects of the various PCSs to reduce heat stress of athletes, firefighters and construction workers, etc. [13,27], or improving thermal comfort of office workers [28]. However, no meta-analysis study was performed for examining the usability of PCSs for medical workers. Thus, the effectiveness and usability of PCSs for medical workers were unrevealed. Though most PCSs were mainly examined for other people group, some has strong feasibility on medical workers such as liquid cooling clothing that could also be worn under PPE [19].

In view of the above, using meta-analysis method, this paper systematically analyzed the effects of different PCSs in reducing body heat stress and improving body thermal perception as well as their possible applications to medical workers. In addition, ergonomic issues of the PCSs during practical use were also analyzed. The findings of this study will provide solid evidence to identify the optimal PCSs for medical workers in terms of alleviating heat stress, improving thermal perception and showing user-friendliness under high ambient temperatures.

2. Methods

This review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [31]. The statement is an evidence-based minimum set of items for reporting in systematic reviews and meta-analyses, and could help reviewers to improve the quality of the review. The statement includes a checklist and a standardized four-phase flow diagram (i.e., identification, screening, eligibility and inclusion) listing the selection process. It can be used to assess interventions [31], and in this study, PCSs are the interventions introduced to reduce heat stress and improve thermal perception of human body.

2.1. Literature research

Extensive literature search was conducted in the following databases: Google Scholar, Web of Science, Science Direct and Scopus (Table 1). The following keywords were used to pick out the potential publications in all the databases: personal/individual cooling strategies, cooling clothing, cooling system, cooling chair, cooling drinks, water immersion, thermal/heat stress thermal perception and thermal comfort. To get most relevant studies, the retrievals were systematically conducted by combining the above keywords using Boolean operators ‘‘AND” and ‘‘OR”. In addition, additional publications including review articles were tracked by examining the references listed in the searched results. To avoid possible omissions, the research was continued until the paper was submitted to a journal.

2.2. Selection criteria

A great number of studies were obtained through extensive literature research. The publication selection process is shown in Fig. 1. Firstly, studies that were not expressed in English, and those only included abstracts and unpublished were excluded. Thereafter, publications are selected based on the objective of this study.

1) PCSs were assessed in moderately warm, warm and hot conditions, respectively (> 26 °C);
2) PCSs were evaluated by having participants performing sitting, standing or performing aerobic exercise;
3) The studies examined one or more PCSs that have potential applications on medical workers;
4) Studies compared the effects of cooling (PCSs) and no cooling condition (CON) by arranging randomized controlled trials;
5) Studies that used external air fans based on convective thermal transfer such as desk air fans, air cooling chairs incorporated with air fans and air nozzles mounted on furniture were considered ineffective for medical workers, thus excluded;
6) Participants employed in the studies are healthy, without disability or disease that affects body thermoregulation, and the aged participants were excluded;

7) Studies that reported participants' physiological (i.e., core body and skin temperatures) and thermal perceptual responses (i.e., thermal sensation and comfort sensation) at the end of the protocol as well as human performance with sufficient quantitative information (e.g., means, standard deviations, the number of participants) were used to calculate the effect sizes of the various PCSs. It is worth noting that some studies provide variation such as standard error, confidence intervals and interquartile ranges, and to obtain effect size, converting them to standard deviation is necessary [32]. Studies that did not give enough information for calculating effect size were excluded.

The quality of the selected literature was then evaluated according to the Physical Therapy Evidence Database (PEDro) scales, which were widely used to assess the methodological quality of clinical trials [33]. The eleven items listed in PEDro (i.e., eligibility criteria and source of subjects specified, produced a total score of 10 with the first item not specified. In fact, it is often impossible to

Table 1
Literature search in the databases.

Database	Search phrase	Search period
Google Scholar	Personal/individual cooling strategies, cooling clothing, cooling system, cooling chair, cooling drinks, water immersion, thermal/heat stress, thermal perception, and/or thermal comfort	1920–2023
Web of Science		1949–2023
Science Direct		1949–2023
Scopus		1949–2023

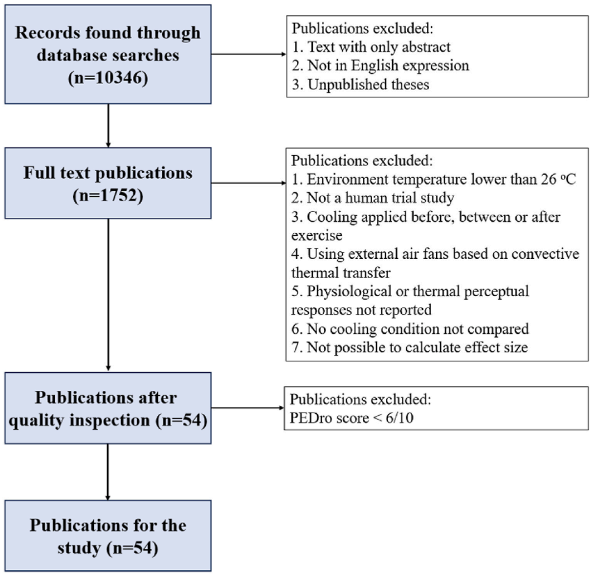

Fig. 1. Selecting process of the publications.

completely blind the cooling strategies to the subjects, therapists or evaluators, hence the maximum score of PEDro is 7 [34]. Publications with a score no lower than 6 are considered to be of high quality. Two reviewers marked the publication, and a panel meeting was held if there was a disagreement.

2.3. Study classification

The included studies were classified according to the types of PCSs for further analysis.

1) Cooling strategies were divided into internal body cooling (IBCSs) [20,35,36] and external body cooling strategies (EBCSs) [15–18,20,22,23,35–81]. It is noted that IBCS involves ice slurry or ice water intake at the beginning of test, and EBCS includes using personal cooling wearables or devices during the whole test.
2) According to different cooling methods, EBCSs were further divided into five categories: liquid cooling clothing (LCC) [16,17,38–48,81], air cooling clothing (ACC) [40,49–57,81], phase change cooling clothing (PCMC) [18,20,37,41,43,45,51,52,58–71], hybrid cooling clothing that combined two or more aforementioned cooling clothing strategies (HCC) [22,23,44,51,58,72–76] and semiconductor cooling devices incorporating with cooling pads (SCDs) [15,77,78]. It is noted the EBCSs except SCDs involve cooling clothing, cooling coveralls and cooling headwear. SCDs include cooling seats, cooling clothing and cooling wristbands incorporated with semiconductor cooling pads.

2.4. Statistical analyses

For all included studies, the effect size (standardized mean difference) and 95 % confidence intervals (95 %CI) were calculated to assess the cooling effectiveness of PCSs. The bias-corrected hedge's effect sizes (EFS) were employed to overcome the disadvantage of small sample sizes using the Review Manager V.5.4.0 software (RevMan version 5.4.0, Cochrane, London, UK). Mean and standard deviation values of thermophysiological and perceptual parameters (i.e., core temperature, skin temperature, heart rate, whole-body thermal sensation, whole-body thermal comfort or rating of perceived exertion) or human performance are required for each study. Besides, sample size is required for all studies. If the parameters were only presented in the figures, GetData digital digitizer software is used to extract them, which are further checked by another author. When only standard error values were presented in the studies, standard deviation values can be obtained by multiplying the standard error by the square root of the sample size. In addition, if important data are missing, attempts are made to contact the authors for obtaining the data.

Further, publication bias was evaluated using Egger's funnel plot, which was widely used to assess the differences in studies. It describes the relationship between the EFSs and the standard deviation of EFSs. EFSs in the range of 0–0.19, 0.2–0.49, 0.5–0.79, and higher than 0.8 represent negligible effect, small effect, moderate effect and large effect, respectively [82].

Statistical heterogeneity (using I^2 statistics) was used to determine the percentage of the variability in effect estimates. When moderate (50 % $< I^2 <$ 75 %) or high heterogeneity ($I^2 >$75 %) was detected, a random-effects regression model was adopted to calculate the pooled intervention effect. Otherwise, a fixed effect inverse variance method was used to calculate the intervention effect [83]. The weighted average effect sizes were calculated on the basis of each study's weighting. In addition, group differences were presented as p values, and statistically significant differences were set as $p < 0.05$ [84].

3. Results

3.1. Included studies

High-quality publications with PEDro scores higher than 6 were listed in Appendix A. Following the selection process, a total of 54 publications (including 53 journal articles and 1 conference paper) were finally identified to meet all inclusion criteria. Appendix B presents a summary of these publications, including the authors and the year, cooling strategies, sample sizes, environmental conditions and testing protocols, and effect sizes of the PCSs.

It is noted that several papers compared multiple PCSs in a single or multiple environments, examined a single PCS in multiple environments or used several exercise protocols for examining a PCS under a single environment. A total of 85 studies were involved in the 54 publications. Also, 556 subjects participated in these studies. The sample size ranges from 4 to 30, and the average sample size is 10. Besides, 44 studies employed only male subjects, 4 studies used female subjects and 6 studies employed both male and female subjects. Of the 54 publications, 4 were conducted in multiple environment settings. Therefore, a total of 57 environmental scenarios were discriminated, with air temperatures varying between 26 °C and 55 °C and relative humidity between 13 % and 80 %.

Regarding to the acquisition of physiological and perceptual parameters in the studies, core temperature was measured by inserting a thermistor into the rectum or using an ingestible capsule sensor; Mean skin temperature was obtained by measuring a number of skin points; Thermal sensation was assessed using ASHRAE 7-point scale (i.e., cold, cool, slightly cool, neutral, warm, slightly warm, warm and hot) or 9-point scale (i.e., very cold, cold, cool, slightly cool, neutral, warm, slightly warm, warm, hot, and very hot); Thermal comfort was evaluated using 4-point scale (i.e., comfortable, slightly comfortable, uncomfortable, and very uncomfortable) or 5-point scale (i.e., comfortable, slightly uncomfortable, uncomfortable, very uncomfortable and extremely uncomfortable); Rating of exertion (RPE) was assed using the scale that ranges from 6 to 20, where 6 means "no exertion at all" and 20 means "maximal exertion". Apart from the above parameters, human performance was also used to assess the benefits of PCSs. Human performance, mainly related to human thermopsychology and physiology, refers to the performance of jobs, tasks and activities by human body [14]. It was measured using the indicators of endurance, speed, power output, manual dexterity, reaction time and accuracy [13,14].

3.2. Publication bias

The publication bias of 85 studies was examined by using funnel plots (Fig. 2). This plot presents the relationship between EFSs and the standard errors of EFSs. Considering that most studies involved the data of skin temperature serving as an important parameter to assess human heat stress, the publication bias was assessed using all the studies including skin temperature. It is revealed from the plot that there exists publication bias, supported by the insignificant Egger test ($p > 0.05$) and Begger's test ($p > 0.05$). Two studies that examined LCC were detected to cause the bias, but they were still involved in the analysis to get additional information on the effects of PCSs. Heterogeneity test showed these studies have acceptable moderate heterogeneity with an I^2 value of 52 %. Therefore, the random effects model was adopted to calculate the EFSs of PCSs.

3.3. The effects of IBCS and EBCS

3.3.1. Human thermophysiological responses

Fig. 3 displays the forest plot of the EFSs for the effect of different types of PCSs on body core temperature and mean skin temperature. EBCSs demonstrated large effects in reducing body core temperature (EFS = 0.99, 95 % CI: 0.79 to 1.20, n = 53) and mean skin temperature (EFS = 1.71, 95 % CI: 1.31 to 2.11, n = 53). Whereas, IBCSs only exhibited moderate effect on body core temper-

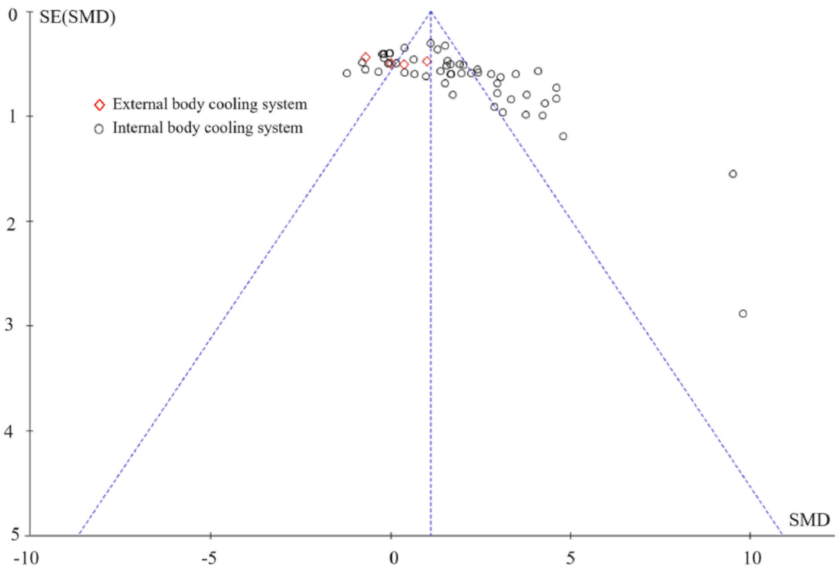

Fig. 2. Funnel plot.

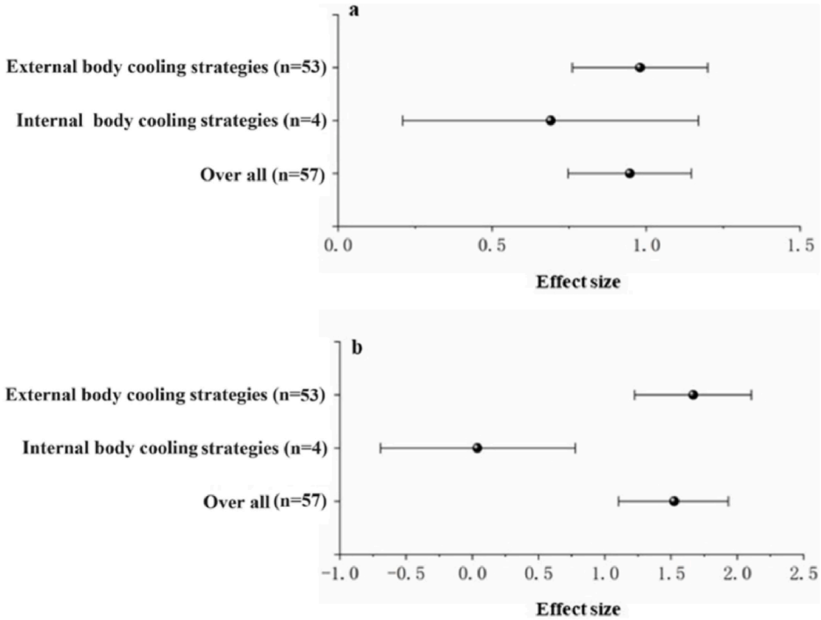

Fig. 3. The forest plot of the hedge's effect sizes for the effects of different types of personal cooling systems on core temperature (a) and mean skin temperature (b).

ature (EFS = 0.69, 95 % CI: 0.21 to 1.17, n = 4), and small effects on both mean skin temperature (EFS = 0.15, 95 % CI: −0.58 to 0.89, n = 4). EBCSs showed remarkably greater effects on the thermophysiological parameters than IBCSs ($p < 0.05$).

3.3.2. Thermal perceptual responses

Fig. 4 shows the forest plot of the hedge's effect sizes for the effect of different types of PCSs on whole-body thermal sensation, whole-body thermal comfort and RPE. EBCSs displayed large effects on both thermal sensation (EFS = 1.23, 95 % CI: 0.94 to 1.51, n = 46) and thermal comfort (EFS = 1.05, 95 % CI: 0.77 to 1.32, n = 29), and a moderate effect on RPE (EFS = 0.54, 95 % CI: 0.34 to 0.75, n = 19). IBCSs only showed small benefits in improving thermal sensation (EFS = 0.04, 95 % CI: −0.57 to 0.64, n = 2), thermal comfort (EFS = 0.08, 95 % CI: −0.80 to 0.95, n = 1) and RPE (EFS = 0.38, 95 % CI: −0.23 to 0.99, n = 2). EBCSs manifested remarkably greater benefits in improving thermal sensation and thermal comfort than IBCSs ($p < 0.05$).

3.3.3. Human performance

In the included studies, human performance was measured using tolerance time, which refers to a period of time from the beginning to the end of the experiment when the one of the termination criteria was satisfied (e.g., reaching 90 % of maximal heart rate, rectal temperature exceeding 39.0 °C, or reaching the specified experimental duration). Fig. 5 exhibits the forest plot of the hedge's effect sizes for the effect of different types of PCSs on human performance. EBCSs (EFS = 1.14, 95 % CI: 0.80 to 1.48, n = 23) significantly improved human performance, while IBCSs displayed a slight effect (EFS = 0.20 95 % CI: −0.68 to 1.08, n = 1).

3.4. The effects of different types of EBCSs

3.4.1. Core temperature

Fig. 6 depicts the effects of various types of EBCSs on body core temperature. Large effects of LCC (EFS = 1.68, 95 % CI: 1.10 to 2.26, n = 13), ACC (EFS = 0.88, 95 % CI: 0.48 to 1.29, n = 12), HCC (EFS = 0.83, 95 % CI: 0.53 to 1.13, n = 11) and PCMC (EFS = 0.8, 95 % CI: 0.48 to 1.12, n = 17) were discovered in reducing body core temperature. In addition, LCC was detected to have a larger effect than the rest EBCSs ($p < 0.05$).

3.4.2. Mean skin temperature

Fig. 7 presents the effects of various EBCSs on body mean skin temperature. There are large effects in reducing mean skin temperature using LCC (EFS = 3.04, 95 % CI: 1.71 to 4.38, n = 10), ACC (EFS = 2.02, 95 % CI: 0.92 to 3.12, n = 10), PCMC (EFS = 1.33, 95 % CI: 0.80 to 1.86, n = 24) and HCC (EFS = 1.47, 95 % CI: 0.38 to 2.57, n = 7). SCD had small effects in reducing mean skin temperature (EFS = 0.39, 95 % CI: −0.31 to 1.09, n = 1). Besides, LCC manifested dramatically larger benefit in reducing mean skin temperature than the rest EBCSs ($p < 0.05$).

3.4.3. Thermal sensation

Fig. 8 displays the effects of different types of EBCSs on human thermal sensation. LCC (EFS = 3.04, 95 % CI: 1.11 to 3.83, n = 6), ACC (EFS = 1.94, 95 % CI: 0.72 to 3.16, n = 7), HCC (EFS = 1.65, 95 % CI: 0.85 to 2.44, n = 6) and SCD (EFS = 0.96, 95 % CI: 0.56 to 1.36, n = 7) manifested large effects in improving human thermal sensation. PCM had a moderate effect

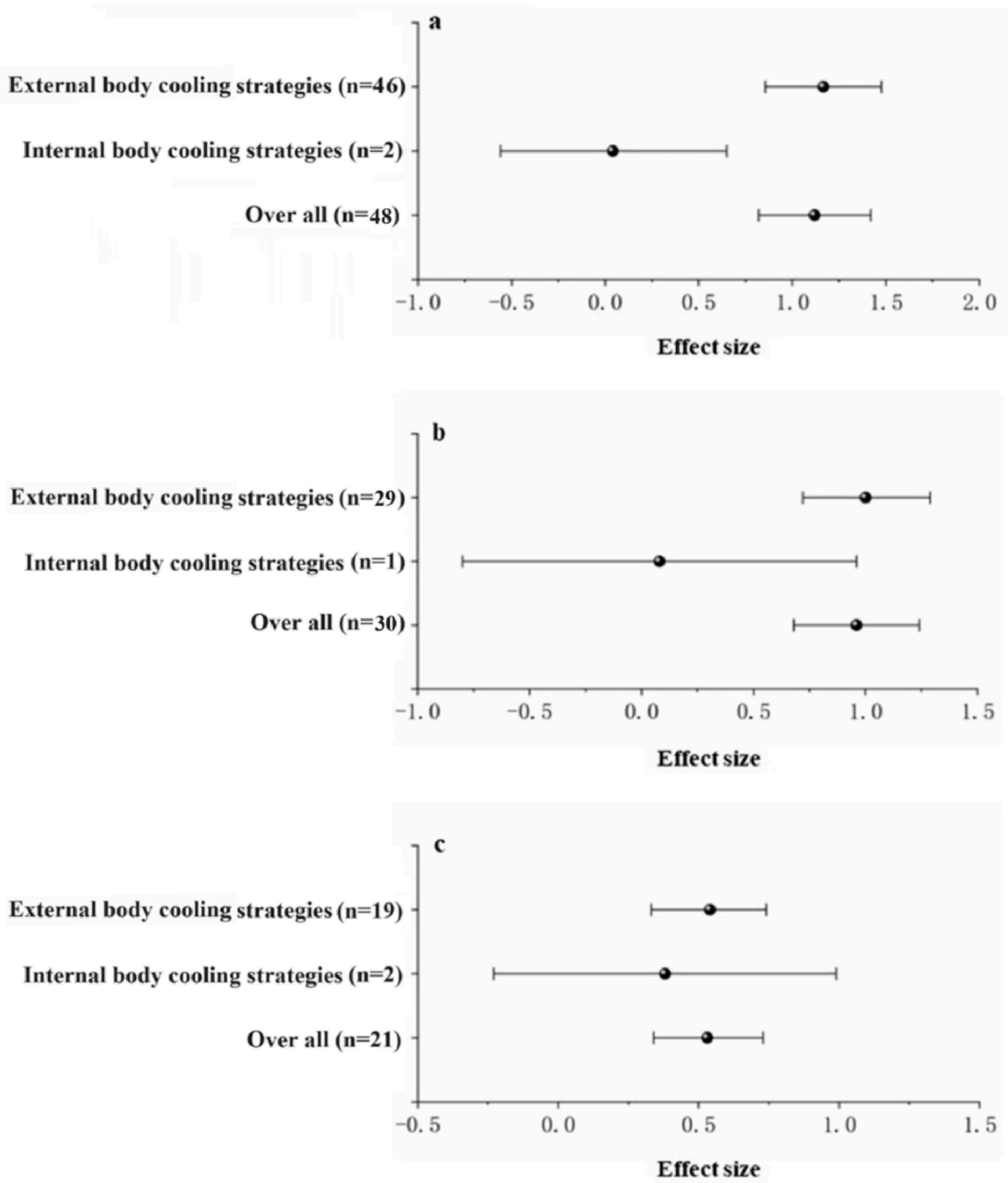

Fig. 4. The forest plot of the hedge's effect sizes for the effects of different types of personal cooling systems on whole-body thermal sensation (a), whole-body comfort sensation (b) and rating of perceived exertion (c).

(EFS = 0.77, 95 % CI: 0.36 to 1.19, n = 19). It is also discovered LCC exhibited remarkably great benefit than the rest EBCSs ($p < 0.05$), and ACC and HCC showed significantly larger effects than SCD and PCMC ($p < 0.05$).

3.4.4. *Comfort sensation*

Fig. 9 shows the effects of the various types of EBCSs on human comfort sensation. LCC (EFS = 2.74, 95 % CI: 1.02 to 4.46, n = 5) exhibited and substantially larger effect on comfort sensation than ACC (EFS = 1.39, 95 % CI: 0.36 to 1.96, n = 6), HCC (EFS = 1.17, 95 % CI: 0.68 to 1.66, n = 6), PCMC (EFS = 0.67, 95 % CI: −0.02 to 1.36, n = 5) and SCD (EFS = 0.68, 95 % CI: 0.37 to 1.00, n = 6) ($p < 0.05$). ACC and HCC manifested large effects, while PCMC and SCD demonstrated moderate effects.

3.4.5. *Rating of perceived exertion (RPE)*

Fig. 10 presents the effects of the various types of EBCSs on RPE. LCC displayed a large effect in improving human RPE (EFS = 0.80, 95 % CI: 0.35 to 1.24, n = 4). ACC displayed a moderate effect (EFS = 0.66 95 % CI: 0.10 to 1.21, n = 6).

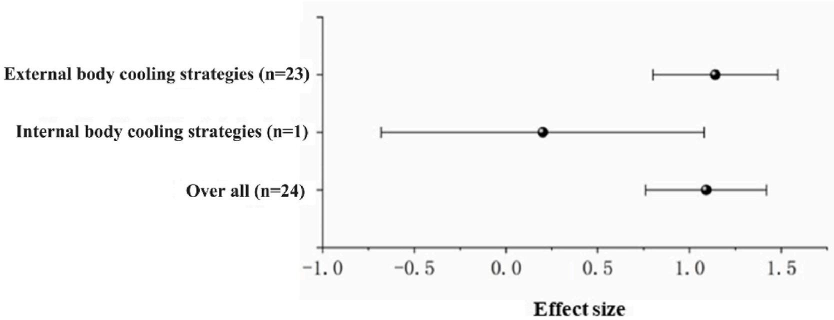

Fig. 5. The forest plot of the hedge's effect sizes for the effects of different types of external personal cooling systems on human performance.

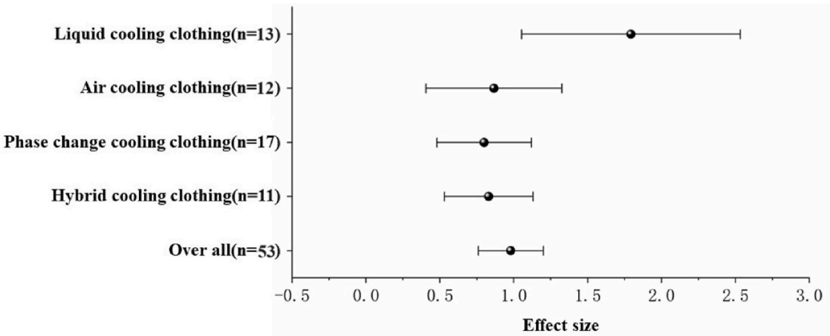

Fig. 6. The forest plot of the hedge's effect sizes for the effects of different types of external personal cooling strategies on core temperature.

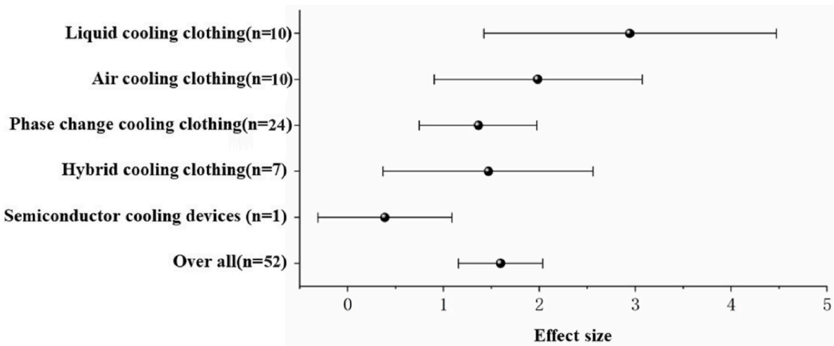

Fig. 7. The forest plot of the hedge's effect sizes for the effects of different types of external personal cooling strategies on skin temperature.

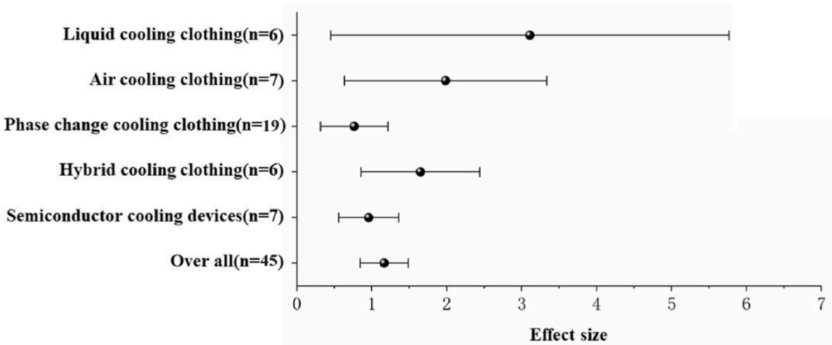

Fig. 8. The forest plot of the hedge's effect sizes for the effects of different types of external personal cooling strategies on thermal sensation.

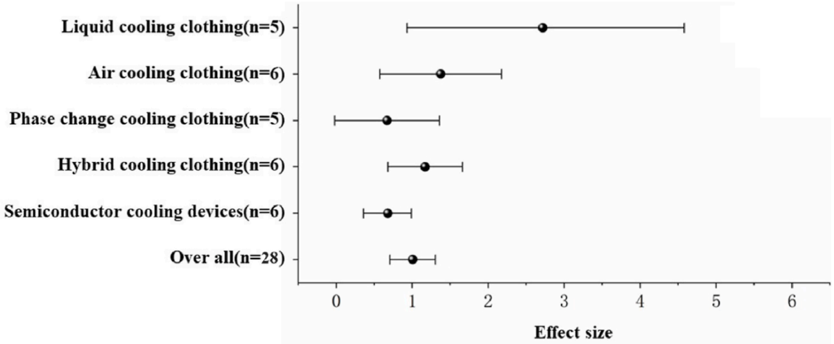

Fig. 9. The forest plot of the hedge's effect sizes for the effects of different types of external personal cooling strategies on comfort sensation.

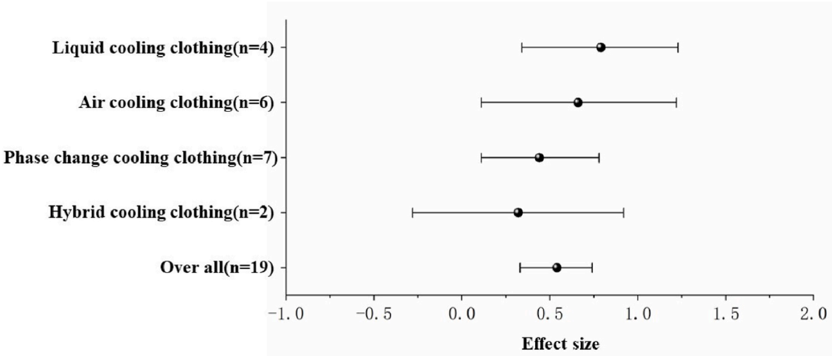

Fig. 10. The forest plot of the hedge's effect sizes for the effects of different types of external personal cooling strategies on rating of perceived exertion.

Whereas, PCMC (EFS = 0.44 95 % CI: 0.10 to 0.77, n = 7) and HCC (EFS = 0.32 95 % CI: −0.28 to 0.92, n = 2) demonstrated small benefits.

3.4.6. Human performance

Fig. 11 shows the effects of the various types of EBCSs on human performance. LCC (EFS = 1.16, 95 % CI: −0.02 to 2.35, n = 4), ACC (EFS = 1.50, 95 % CI: 0.74 to 2.25, n = 5), PCMC (EFS = 0.80, 95 % CI: 0.35 to 1.26, n = 8) and HCC (EFS = 1.35, 95 % CI: 0.67 to 2.03, n = 6) all had large effects in improving human performance. It is also discovered that PCMC (EFS = 0.80, 95 % CI: 0.35 to 1.26, n = 8) exerted remarkably less benefit compared to other types of EBCSs ($p < 0.05$).

4. Discussion

In this study, a meta-analysis study was performed to find the appropriate PCSs for medical workers, and various PCSs from published papers that has potential applications to the group were compared and analyzed. It is found that external body cooling strategies (EBCSs) manifested remarkably larger cooling benefits than internal body cooling strategies (IBCSs). Furthermore, liquid cooling clothing (LCC) was discovered to exhibit substantially larger cooling benefit compared to other types of EBCSs in improving body

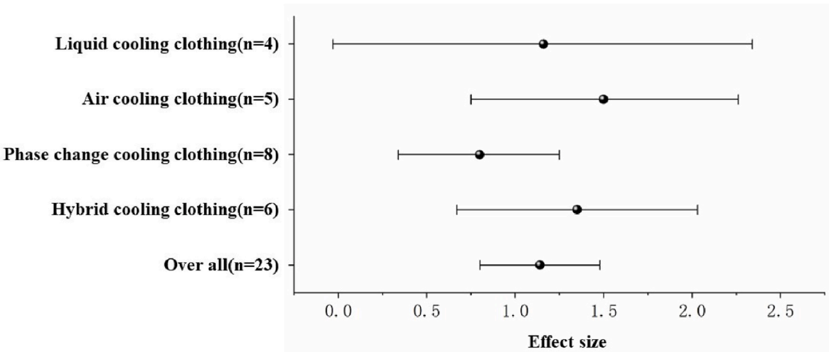

Fig. 11. The forest plot of the hedge's effect sizes for the effects of different types of external personal cooling strategies on human performance.

thermophysiological and thermal perceptual responses. Furthermore, LCC demonstrated a large benefit in improving the rating of perceived exertion (RPE), whereas the rest EBCSs exhibited small to moderate effects. Air-cooling clothing (ACC) and hybrid cooling clothing (HCC) also demonstrated large cooling benefits in improving body thermophysiological and perceptual responses. Phase change material clothing (PCMC) exhibited large and moderate benefits in improving body thermophysiological and thermal perceptual response, respectively. Semiconductor cooling devices (SCDs) presents moderate to large effect in improving human thermal perceptual response. In addition, all EBCSs present large beneficial effects in improving human performance and PCMC showed remarkably the least benefit in improving human performance.

4.1. Effectiveness of IBCSs and EBCSs

Statistical analysis shows that IBCS showed moderate effect in reducing body core temperature. After intaking cold ice or water, coolness spreads through the body via the oral cavity, esophagus, stomach and the intestines, possibly reducing body temperature. Besides, using IBCSs could promote conductive heat transfer inside the body. The attenuated core temperature could reduce the amount of body heat storge, possibly explaining the moderate human performance improvement using IBCSs. There are also studies pointing out that cold liquid intake could excite pleasure/reward in the brain centers, inducing great motivation for exercise and thus improving human performance. In contrast, the negative effect of IBCSs was also pinpointed by studies that sweat loss was significancy suppressed using this strategy, hindering the primary evaporative heat loss avenue to for body cooling in hot environments [85,86]. However, the adverse effect of IBCSs was minimized for human body wearing thick PPE or humid environments where sweat evaporation was greatly suppressed [20]. In this study, the three publications included examined IBCSs for human body in PPE and humid enlivenments [20,35,36]. The above may possibly explain the moderate effect of IBCSs in reducing body core temperature. However, using IBCSs before exercise could not alter the change of skin temperature and perceptual responses, possibly because of the short actuation duration of the cooling water or ice. It is also reported that the benefits of pre-cooling are often lost during prolonged exercise [87,88].

Applying EBCSs was discovered to exert large benefits in reducing body thermopsychological and thermal perceptual responses. These EBCSs function on the principle of promoting thermal dissipation to the ambient via conductive, convective, radiative, evaporative or the combined thermal transfer mechanism. These EBCSs often targeted at the face/head, the torso or the above two regions. It is consistently reported that cooling the head/face is more efficient than cooling other body parts per unit surface area, which attributed to the abundant blood supply in the head, leading to a great amount of heat loss, and high sudomotor thermosensitivity to face cooling, greatly suppressing sweating at the facial area [89,90]. It is also detected that the torso region is the ‘‘most influential group”, owning to its larger cooling area, greater vascularization, and greater number of cold receptors located at this region, and EBCSs that targeted at this region are more effective than those that only covered face/head. In this review, most EBCSs targeted at more than two regions involving the torso part, which may interpret their large benefits. The improved thermopsychological and thermal perceptual responses using EBCSs induced the significant improvement of human performance. RPE was mainly related to human activity intensity, possibly accounting for the moderate improvement of the parameter.

4.2. The effects of the various types of EBCSs

LCC was discovered to impose significantly benefits in improving human thermophysiological and thermal perceptual responses than other types of EBCSs. Generally, LCC was constructed by embedding tubes with circulating cold water in clothing that tightly fits human body. The large benefit of LCC was possibly due to the following reasons: 1) the low water temperature in the liquid tubes, normally ranging from 5 to 18 °C, greatly enables body heat loss to the ambient environment, 2) the large coverage area of liquid tubes could greatly promote heat loss from human body, and 3) the liquid tubes are mostly placed on the body torso, which is more sensitive to cold stimulus. Considering this, it is not surprising to find the more remarkable improvement of human physiological and perceptual responses in LCC.

ACC also displayed a large cooling benefit in improving human physiological and perceptual responses. It mainly stimulates natural or dry air around human body to promote evaporative heat loss [91]. Using PCMC only has a large effect in improving thermophysiological responses. This was likely due to that the cooling effect of PCMC becomes weaker after the phase transition and normally disappeared within about 30 min after the test. As the involved studies concerning HCC consists of small air fans and PCM packs, it is thus not surprising to find that HCC showed large effect in improving human thermophysiological and thermal perceptual responses.

SCD displayed a large effect in improving body thermal sensation, while a moderate effect on thermal comfort. The SCD included in this study were mainly constructed by incorporating a thermoelectric cooling pad into chairs or clothing. The thermoelectric pad comprised of two different thermoelectric materials connected in series is based on Peltier-Setback effect, which creates cooling and heating at both ends of the device when direct current is passed through it. This cooling method was rapid, steady and could create much lower surface temperature adjacent to human body, which may account for the large benefit of SCD in improving body thermal sensation. Compared with other types of PCSs, SCD only targeted at a small body surface region (such as buttocks, chest or back), and often induced local discomfort due to the ‘overcooling’ in the cooled regions frequently reported in documented studies, which may possibly explain the moderate effect of SCC in improving thermal comfort.

LCC displayed a large benefit in improving RPE, and the rest EBCSs only exhibited small to moderate effect in improving RPE. Previous studies consistently discovered that RPE is highly related to exercise intensities and moderately related to thermal comfort. The significant improvement on RPE of LCC is possibly because its’ substantial cooling effect. Whereas, the nonremarkable effect of the rest EBCSs on RPE was likely that the body thermal comfort improvement brought by them was insufficient to produce large benefits.

Using the various PCSs showed large benefit in improving human performance. Previous studies consistently discovered that cooling prior aerobic exercise or during aerobic exercise could attenuate the increase in core temperature, increase heat storage capacity and improve exercise capacity [87,92]. Besides, some research studies also postulated that cooling benefited RPE and thermal perception also contributed greatly to human performance during the fixed-intensity exercise and self-spaced aerobic exercise [93,94]. The large benefit of the various PCSs on human performance may arise from the significantly improved physiological and perceptual responses. Though LCC displayed larger cooling benefit in improving human physiological and perceptual responses, it did not show more significant improvement in human performance. It is consistently reported by researchers that the weight applied on body could decrease human performance, with 2.4 %–3.5 % performance reduction per kilogram [95]. Besides, the tight fit of LCC that makes it works may restrict body movement during exercise [96]. The high load carriage of human body (normally ranging from 3 to 10 kg) and the ergonomic issues when wearing LCC may aggravate human performance. The effect of LCC on RPE and human performance was not revealed in current studies.

4.3. Practical application for medical workers

Compared to other occupational workers such as construction workers, medical workers in PPE are more prone to suffer the risk of uncompensable heat stress in high ambient temperatures due to 1) the greatly restricted heat dissipation from body to the ambient due to the impermeability of PPE, 2) the less heat loss or even dry heat gain when the ambient temperature exceeding the body skin temperature, and 3) the increased heat production due to the prolonged work hours, especially for some types of medical work such as nucleic acid testing work and emergency surgeries. Exploring the effective PCSs for reducing heat stress of the group is of great needed. In addition, during the actual application of EBCSs, ergonomics issues of adopting the PCSs such as weight, mobility, convenience of use as well as the compatibility between EBCSs and PPE, the work types and work environments of medical workers should be fully considered.

In this study, using IBCSs was discovered to exert moderate effect in reducing body core temperature, representing thermal strain could be alleviated using this method. The included studies all examined IBCSs adopted aerobic exercise lasting between 30 min and 60 min [20,35,36]. It is supported by previous studies that frequently ingesting ice slurry or cold liquid could have better benefit in alleviating body heat stress. Using IBCS may be feasible for medical workers confronted with severely high ambient temperatures where cooling demand is greatly needed. Using IBCS before putting on PPE is feasible and effective to assist alleviating body thermal strain. It is also supported that the cooling effectiveness of IBCSs could be lost during prolonged exercise, which may be not convenient for medical workers working for several hours due to the frequent taking off and putting on of the protective masks, may increasing the risk of virus infection. Besides, it may cause gastrointestinal discomfort, especially those with gastrointestinal diseases. In view of these, using EBCSs instead of IBCS may be a relatively safer and more feasible to combat heat stress.

LCC was normally comprised of a tight-fitting vest stitched with soft liquid tubes circulated with cold water (i.e., a liquid cooling vest), a refrigeration compressor placed nearby human body or a backpack filled with ice water that supply cold water to the vest, a micro-pump, and a power source. The weight of such cooling system is heavy, normally ranging from 3 kg to 10 kg, which may impose great burden on human body, and restrict human mobility. In spite of this, it is highly expected that LCC was applicable for medical workers continuously working for several hours in high ambient environments, who are very susceptible to uncompensable heat stress. In such cases, for medical workers with less body movement and fewer postures such as nucleic acid sample collection personnel and surgical doctor, using LCC with a refrigeration compressor nearby may be more applicable as the weight-related issues is no longer prominent; whereas, for medical workers with frequent body movement such as environmental cleaning and disinfection personnel, LCC using a cooling backpack as the cooler with relatively low weight (around 3 kg) is more suitable, but it suffers the shorter cooling duration. In addition, the liquid cooling vest of LCC was suggested to wear under PPE due to: 1) the loose-fitting design of PPE benefiting for body movement was not destroyed; 2) its cooling efficiency may be maximized due to the close contact with body skin. It is also noted that the interface between liquid tubes and PPE should be fully sealed.

ACC typically uses mini air fans or flexible air tubes with small holes connected with an air-cooling device to provide air ventilation around human body, promoting convective & evaporative heat loss. This method was found to produce large benefit in combating heat stress, and possessed the advantages of long and steady cooling duration [97]. Compared with LCC, ACC weighted much lighter (0.6–1.2 kg) and it does not need to contact closely with human body, producing less ergonomic issues [13]. During practical use, modification of PEE is required to incorporate the air-cooling system while satisfying the virus protection standards. It may be possible to construct ACC for medical workers by circulating filtered natural air or cold air from the ambient. In fact, such products have already been used for medical workers during the fighting against novel coronavirus. Similar to the application of LCC, ACC with an air-cooling device placed nearby may be more applicable for medical workers with less body movement and fewer postures, and an air filtration system should be connected to the device before sending the clean air into the microclimate between human body and PPE. ACC using air fans may be more suitable for medical workers with large range motion. Air fans should be well incorporated into PPE, and an air filtration fabric overlaying on the top of the air fans should be spliced with PPE. In addition, air outlet should also be designed on PPE. It is also noted that ACC may be very bulk due to air blowing, which may impair the performance of medical work with high operational accuracy such as the operating crew. In view of this, the effectiveness and ergonomic evaluation of ACC should be performed in future studies due to the lack of such studies.

PCMC was constructed by incorporating PCM packs into the pockets of the garment. It was discovered to have cooling benefit in reducing body thermal strain, and it is also relatively light (around 1–2 kg), requires no power supply and easy to use. However, the cooling duration of PCMC is very limited (normally within 30 min), and replacement of PCM packs are required to keep it effective for prolonged work. The cooling strategy may be feasible for medical workers with relatively short working time or applicable for medical workers who have chance to replace PCM packs during long hour work. A recent study by de Korte [29] examined the usability of PCMC for nurses wearing PPE who work about 3 h a day separated by three breaks, and they could change PCM packs that are stored in the refrigerator in the virus free room during the breaks. HCC was generally comprised of PCM packs and air-cooling systems. It demonstrates similar cooling benefit to ACC, but suffered more ergonomic issues due to the more complicated system. It is thus not recommended.

SCD incorporates semiconductor cooling pads into chairs or clothing, displaying cooling benefit in improving body thermal perception. The cooling method is steady and fast, as it is based on conductive thermal transfer mechanism. However, a heat dissipating system was required to dissipate the heat generated on the hot surface of the semiconductor chip such as heat exchangers, water tank and water pump, which need to occupy extra space. SCD may be suitable for medical workers with less movement. SCD in the form of cooling chairs may be very suitable for medical workers performing sedentary work, as it suffers very less ergonomic issues.

Apart from the above issues, understanding the energy consumption of the various PCSs helps to select the energy-efficient strategies with long duration. Only two publications exactly reported the energy consumption of SCD with one ranging from 65 to 110 W in 25 min [77], and one rated as 45 W in 40 min [16]. The energy consumption of ACC using air fans can also be estimated based on several studies, which ranges from 6 to 11 W in 120 min [52,54,55]. One study reported that LCC powered by ice water source consume less than 55 W in 45 min [17]. Though not reported, PCM packs should be stored in the refrigerator which also requires energy consumption. It seems that SCD has much larger energy consumption than other types of PCSs, which is very likely because of the low energy efficiency of the current semiconductor cooling method [98]. It still may be a choice for medical staff in hot environments where cooling demand is strong. ACC may have much lower energy consumption. However, the exact energy consumption of the various PCSs should be compared in the same testing scenarios.

Regarding to the workplaces where PCSs are applicable for medical workers, nonportable LCC and ACC are suitable to be used in indoors or around buildings where power source is attainable. Portable LCC and ACC are applicable for various working locations. PCMC are more suitable for medical workers in locations where virus free rooms exist, storge and replacement of PCM packs are possible. The use of the above PCSs in indoors was likely to save building energy consumption while maintaining thermal comfort of medical workers. Due to high energy consumption, SCD was recommended to be used around buildings in case of high ambient temperatures. IBCSs were suggested to be utilized in outdoors with high ambient temperatures.

In future studies, apart from the cooling benefit, attention should be paid to the ergonomic issues and energy consumption relating to PCSs, and the possible application of PCSs to the working scenarios of medical workers. Besides, the energy saving performance of the various PCSs should be also examined for indoor medical workers with the purpose of promoting building energy efficiency. In addition, more PCSs should be developed based on AI technology that could noninvasively capture the real-time personal data and automatically control the PCS to satisfy individual thermal demand.

4.4. Limitations and future perspectives

The aim of this meta-analysis study is to examine the effects of various PCSs on human physiological and psychological responses as well as human performance, and to identify the "best practice" for medical workers. The reliability of this study relies on the selection criteria, the quality of the studies, and the extent to which the information from these studies can be integrated. However, several limitations must be admitted.

Firstly, only studies written in English are included, which may possibly lead to research omissions, and result in publication bias. In fact, publication bias was observed because a small number of negative results were reported. Besides the possible omission, positive results are easier to publish, which may exaggerate the cooling effectiveness of PCSs.

Secondly, there exist procedure differences among the various studies. The main one is that different subjective judgment scales were used by the various studies to evaluate human perceptual responses using PCSs, which may affect the perceptual results. Besides, the procedures adopted by the studies are different in terms of exercise protocol (e.g., testing duration, exercise intensities), ambient conditions (e.g., temperature, humidity) and subject characteristics (e.g., gender and age). Furthermore, the sample sizes are varied significantly across studies. These are the key barriers to make direct comparisons between the studies. Vallerand et al. [81] examined the effectiveness of a liquid-cooled vest and an air-cooled vest in reducing human strain in 37 °C and 50 %RH. Bach et al. [40] more systematically investigated the effects of a liquid system and air-cooling system with similar cooling capacities in reducing human thermal strain using ASTM F2300-10 standard testing protocol and the upper limit of the prescriptive zone for each using critical environmental limits method. It is found that the differences between the two systems could not be delineated in a single environment regulated in ASTM F2300-10 standard, and the upper limits of critical temperature could not be increased by the air-cooling system. The study recommends that a range of environments should be adopted for the evaluation of personal cooling systems to determine the certain environments where the systems are ineffective. In future studies, the cooling effects of the various PCSs for medical workers should be examined in a unified experimental setting under a range of environments or determine the environmental limits where the PCSs are ineffective. In addition, and their energy consumption could be examined as well.

Finally, current studies on the effectiveness of PCSs are mainly laboratory studies, which may differ from their actual performance in real scenarios. In the actual working scenarios, ergonomic issues, physical activities and environmental conditions may greatly affect the effectiveness of PCSs. Viewing this, more field studies should be performed to evaluate the cooling effects of various PCSs for medical workers. In addition, there are few studies involving female subjects in the evaluation of PCSs, but females have different physiological and psychological responses from males. Future studies should also use females to evaluate the effectiveness of PCSs.

5. Conclusion

Using personal cooling strategies (PCSs) provides a feasible way for reducing heat stress of medical workers in PPE, while limited research was found on this topic. Given this, a meta-analysis study was employed to detect the appropriate PCSs for reducing heat stress of medical workers. The practical application of the PCSs to medical workers were analyzed, considering both their cooling effects and ergonomic issues. The following conclusions can be drawn.

1. Using external body cooling strategies (EBCSs) could effectively improve human physiological and psychological responses as well as performance in high temperature environments. Applying internal body cooling strategies (IBCS) only has benefit in reducing body core temperature.
2. Liquid cooling clothing (LCC) was discovered to have the largest cooling benefit. Air-cooling clothing (ACC) and hybrid cooling clothing (HCC) also displayed large and comparable cooling benefits. Phase change cooling clothing (PCMC) and semiconductor cooling devices (SCD) showed less benefits compared to the above cooling strategies.
3. It may be feasible and effective to use IBCS before putting on PPE for medical workers in severely high ambient temperatures outdoors. Nonportable LCC and ACC are more suitable for medical workers in indoors and around buildings who have to work continuously for several hours with less body movements and fewer postures to reduce the ergonomic issues; whereas, LCC using a cooling backpack as the cooler and ACC using air fans was applicable for medical workers with frequent movements working in various locations. When using ACC, air filtration system should be used together. SCD in the form of cooling chairs may be very suitable for medical workers performing sedentary work in hot environments outdoors where cooling demand is strong. PCMC are more preferable for medical workers in the condition where the replacement of PCM packs could be satisfied or the working duration is relatively short.

Our findings contribute to the selection or development of effective and practical PCSs to reduce heat stress of medical workers under various scenarios. The study also provides solid guidelines in choosing appropriate PCSs for other occupational workers.

CRediT authorship contribution statement

Wenfang Song: Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Conceptualization. **Qiuyue Ding:** Writing – review & editing, Investigation, Data curation, Conceptualization. **Mengjiao Huang:** Methodology, Investigation, Formal analysis. **Xinze Xie:** Validation, Supervision, Software. **Xiaoying Li:** Methodology, Investigation, Formal analysis.

Declaration of competing interest

There is no conflict of interest to declare. All authors agree to publish these results.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2024.108685.

References

[1] T. Greenhalgh, M.B. Schmid, T. Czypionka, et al., Face masks for the public during the covid-19 crisis, BMJ 369 (2020) m1435.
[2] K.J. Ruskin, A.C. Ruskin, B.T. Musselman, et al., COVID-19, personal protective equipment, and human performance, Anesthesiology 134 (2021) 518–525.
[3] N. Karim, S. Afroj, K. Lloydet, et al., Sustainable personal protective clothing for healthcare applications: a review, ACS Nano 14 (2020) 12313–12340.
[4] Z. Magdalen, A. Bogdan, Impact of medical clothing on thermal stress of surgeons, Appl. Ergon. 53 (2012) 1096–1104.
[5] N. Shaukat, D.M. Ali, J. Razzak, Physical and mental health impacts of COVID-19 on healthcare workers: a scoping review, Int. J. Emerg. Med. 13 (2020) 1–8.
[6] Y. Kim, Y. Shin, H. Cho, Influencing factors on thermal comfort and biosignals of occupant-a review, J. Mech. Sci. Technol. 35 (2021) 4201–4224.
[7] J. Lee, V. Venugopal, P.K. Latha, et al., Heat stress and thermal perception amongst healthcare workers during the COVID-19 pandemic in India and Singapore, Int. J. Environ. Res. Publ. Health 17 (2020) 8100.
[8] Y. Zhu, S. Qiao, W. Wu, et al., Thermal discomfort caused by personal protective equipment in healthcare workers during the delta COVID-19 pandemic in Guangzhou, China: a case study, Case Stud. Therm. Eng. 34 (2022) 101971.
[9] A. Messeri, M. Bonafede, E. Pietrafesa, et al., A web survey to evaluate the thermal stress associated with personal protective equipment among healthcare workers during the COVID-19 pandemic in Italy, Int. J. Environ. Res. Publ. Health 18 (2021) 3861.
[10] Z. Fang, Y. Mao, Y. Zhu, et al., Human thermal physiological response of wearing personal protective equipment: an educational building semi-open space experimental investigation, Sci. Total Environ. 877 (2023) 162779.
[11] Y. Zhou, L. Lou, J. Fan, Quantitative comparison of personal cooling garments in performance and design: a review, Processes 11 (2023) 2976.

[12] F. Wang, B. Yang, Q. Deng, et al., Personal Comfort Systems for Improving Indoor Thermal Comfort and Air Quality, Springer, 2023, pp. 79–97.
[13] A.P.C. Chan, W. Song, Y. Yang, Meta-analysis of the effects of microclimate cooling systems on human performance under thermal stressful environments: potential applications to occupational workers, J. Therm. Biol. 49 (2015) 16–32.
[14] W.D. McArdle, F.I. Katch, V.L. Katch, in: Exercise Physiology: Energy, Nutrition, and Human Performance, sixth ed., Lippincott Williams & Wilkins, USA, 2007 R.M. Laing, G.G. Sleivert. Clothing, textiles, and human performance. Textile Progress 32 (2) (2002) 1-122.
[15] W. Pasut, H. Zhang, E. Arens, et al., Effect of a heated and cooled office chair on thermal comfort, HVAC R Res. 19 (2013) 574–583.
[16] S.G. Cvetanović, S.Z. Rutić, D.D. Krstić, et al., The influence of an active microclimate liquid-cooled vest on heat strain alleviation, Therm. Sci. 25 (2021) 3837–3846.
[17] A.M. Aljaroudi, A. Bhattacharyab, P. Yorio, et al., Probability of hyperthermia in a hot environment while wearing a liquid cooling garment underneath firefighters' protective clothing, J. Occup. Environ. Hyg. 18 (4–5) (2021) 203–211.
[18] R.E. Reinertsen, H. Færevik, K. Holbø, et al., Optimizing the performance of phase-change materials in personal protective clothing systems, Int. J. Occup. Saf. Ergon. 14 (2008) 43–53.
[19] A.S. Yang, Y.C. Shih, C.L. Lee, et al., Investigation of flow and heat transfer around internal channels of an air ventilation vest, Textil. Res. J. 84 (2014) 399–410.
[20] E.R. Watkins, M. Hayes, P. Watt, et al., Practical pre-cooling methods for occupational heat exposure, Appl. Ergon. 70 (2018) 26–33.
[21] A.R. Hsu, T.A. Hagobian, K.A. Jacobs, et al., Effects of heat removal through the hand on metabolism and performance during cycling exercise in the heat, Can. J. Appl. Physiol. 30 (2005) 87–104.
[22] W. Song, F. Wang, F. Wei, Hybrid cooling clothing to improve thermal comfort of office workers in a hot indoor environment, Build. Environ. 100 (2016) 92–101.
[23] A.P.C. Chan, Y. Yang, W. Song, et al., Hybrid cooling vest for cooling between exercise bouts in the heat: effects and practical considerations, J. Therm. Biol. 63 (2017) 1–9.
[24] C. Gao, K. Kuklane, F. Wang, et al., Personal cooling with phase change materials to improve thermal comfort from a heat wave perspective, Indoor Air 22 (6) (2012) 523–530.
[25] J. Webster, E.J. Holland, G. Sleivert, et al., A light-weight cooling vest enhances performance of athletes in the heat, Ergonomics 48 (7) (2005) 821–837.
[26] A. Ruddock, B. Robbins, G. Tew, et al., Practical cooling strategies during continuous exercise in hot environments: a systematic review and meta-analysis, Sports Med. 47 (2017) 517–532.
[27] J. Li, W. Zhu, Y. Wang, et al., Efficacy of cooling garments on exertional heat strain recovery in firefighters: a systematic review and meta-analysis, Textil. Res. J. 92 (2021) 21–22.
[28] W. Song, Z. Zhang, Z. Chen, et al., Thermal comfort and energy performance of personal comfort systems (PCS): a systematic review and meta-analysis, Energy Build. 256 (2022) 111747.
[29] J.Q. D Korte, C.C.W.G. Bongers, M. Catoire, et al., Cooling vests alleviate perceptual heat strain perceived by COVID-19 nurses, Temperature 9 (1) (2022) 103–113.
[30] L. Lou, Y. Zhou, Y. Yan, et al., Wearable cooling and dehumidifying system for personal protective equipment (PPE), Energy Build. 276 (2022) 112510.
[31] A. Liberati, D.G. Altman, J. Tetzlaff, et al., The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions explanation and elaboration, BMJ 339 (2009) b2700.
[32] J.P.T. Higgins, S. Green, Cochrane Handbook for Systematic Reviews of Interventions: Cochrane Book Series, Willey Online Library, 2008.
[33] A.M. Moseley, M.R. Elkins, P.J.V. Wees, et al., Using research to guide practice: the physiotherapy evidence database (PEDro), Braz. J. Phys. Ther. 24 (5) (2020) 384–391.
[34] E. Albanese, L. Bütikofer, S. Armijo-Olivo, et al., Construct validity of the physiotherapy evidence database (PEDro) quality scale for randomized trials: item response theory and factor analyses, Res. Synth. Methods 11 (2) (2020) 227–236.
[35] S. Onitsuka, X. Zheng, H. Hasegawa, Ice slurry ingestion reduces both core and facial skin temperatures in a warm environment, J. Therm. Biol. 51 (2015) 105–109.
[36] R.R. Pryor, J. Suyama, F.X. Guyette, et al., The effects of ice slurry ingestion before exertion in Wildland firefighting gear, Prehosp. Emerg. Care 19 (2) (2015) 241–246.
[37] C.X. Hu, Z.H. Wang, R.F. Bo, et al., Effect of the cooling clothing integrating with phase change material on the thermal comfort of healthcare workers with personal protective equipment during the COVID-19, Case Stud. Therm. Eng. 42 (2023) 102725.
[38] J.X. Xu, G.L. Chen, X.X. Wang, et al., Novel design of a personal liquid cooling vest for improving the thermal comfort of pilots working in hot environments, Indoor Air (2023) 1–13.
[39] K. Hashimoto, S. Horie, C. Nagano, et al., A fan-attached jacket worn in an environment exceeding body temperature suppresses an increase in core temperature, Sci. Rep. 11 (1) (2021) 21269.
[40] A.J. E Bach, D.N. Borg, G.M. Minett, et al., Biophysical, Psychrometric and Physiological Limits for Continuous Liquid and Air-Based Personal Cooling Systems in Working Men: A Case for Amending ASTM2300-10(2016), vol. 132, 2020 104980.
[41] M.J. Maley, G.M. Minett, A.J.E. Bach, et al., Extending work tolerance time in the heat in protective ensembles with pre-and per-cooling methods, Appl. Ergon. 85 (2020) 103064.
[42] A.M. Aljaroudi, D.S. Kadis, A. Bhattacharya, et al., Effect of continuous cooling on inhibition and attention while wearing firefighter's PPE in a hot environment, J. Occup. Environ. Hyg. 17 (5) (2020) 243–252.
[43] A.J. E Bach, M.J. Maley, G.M. Minett, et al., An evaluation of personal cooling systems for reducing thermal strain whilst working in chemical/biological protective clothing, Front. Physiol. 10 (2019) 424.
[44] F. Wang, C.S.W. Chow, Q. Zheng, et al., On the use of personal cooling suits to mitigate heat strain of mascot actors in a hot and humid environment, Energy Build. 205 (2019) 109561.
[45] T. Quinn, J.H. Kim, Y. Seo, et al., Comparison of thermal manikin modeling and human subjects' response during use of cooling devices under personal protective ensembles in the heat, Prehospital Disaster Med. 33 (3) (2018) 279–287.
[46] J.H. Kim, A. Coca, W.J. Williams, et al., Effects of liquid cooling garments on recovery and performance time in individuals performing strenuous work wearing a firefighter ensemble, J. Occup. Environ. Hyg. 8 (7) (2011) 409–416.
[47] B.S. Cadarette, S.N. Cheuvront, M.A. Kolka, et al., Intermittent microclimate cooling during exercise-heat stress in US army chemical protective clothing, Ergonomics 49 (2) (2006) 209–219.
[48] S.N. Cheuvront, M.A. Kolka, B.S. Cadarette, et al., Efficacy of intermittent, regional microclimate cooling, J. Appl. Physiol. (2003).
[49] C. Graham, G.P. Lynch, T. English, et al., Optimal break structures and cooling strategies to mitigate heat stress during a Rugby League match simulation, J. Sci. Med. Sport 24 (8) (2021) 793–799.
[50] H. Otani, M. Fukuda, T. Tagawa, Cooling between exercise bouts and post-exercise with the fan cooling jacket on thermal strain in hot-humid environments, Front. Physiol. 12 (2021) 640400.
[51] F. Wang, Y. Ke, B. Yang, et al., Effect of cooling strategies on overall performance of a hybrid personal cooling system incorporated with phase change materials (PCMs) and electric fans, J. Therm. Biol. 92 (2020) 102655.
[52] M. Zhao, C. Gao, J. Li, et al., Effects of two cooling garments on post-exercise thermal comfort of female subjects in the heat, Fibers Polym. 16 (2015) 1403–1409.
[53] K.J. Glitz, U. Seibel, U. Rohde, et al., Reducing heat stress under thermal insulation in protective clothing: microclimate cooling by a 'physiological' method, Ergonomics 58 (8) (2015) 1461–1469.
[54] M. Zhao, K. Kuklane, K. Lundgren, et al., A ventilation cooling shirt worn during office work in a hot climate: cool or not, Int. J. Occup. Saf. Ergon. 21 (4) (2015) 457–463.
[55] A. Hadid, R. Yanovich, T. Erlich, et al., Effect of a personal ambient ventilation system on physiological strain during heat stress wearing a ballistic vest, Eur. J. Appl. Physiol. 104 (2008) 311–319.

[56] T.D. Chinevere, B.S. Cadarette, D.A. Goodman, et al., Efficacy of body ventilation system for reducing strain in warm and hot climates, Eur. J. Appl. Physiol. 103 (2008) 307–314.
[57] B.C. Cadarette, W.A. Latzka, L. Levine, et al., A Physiological Evaluation of a Prototype Air-Vest Microclimate Cooling System, US Army Research Institute of Environmental Medicine, Natick, MA, 1760.
[58] U. Raj, F. Wang, W. Song, et al., Performance enhancement of hybrid personal cooling clothing in a hot environment: PCM cooling energy management with additional insulation, Ergonomics 62 (1) (2019) 928–939.
[59] M. Zare, H. Dehghan, S. Yazdanirad, et al., Comparison of the impact of an optimized ice cooling vest and a paraffin cooling vest on physiological and perceptual strain, Safety and Health at Work 10 (2) (2019) 219–223.
[60] M.J. Maley, G.M. Minett, A.J.E. Bach, et al., Internal and external cooling methods and their effect on body temperature, thermal perception and dexterity, PLoS One 13 (1) (2018) e0191416.
[61] C.L. Butts, C.R. Smith, M.S. Ganio, et al., Physiological and perceptual effects of a cooling garment during simulated industrial work in the heat, Appl. Ergon. 59 (2017) 442–448.
[62] W. Yi, Y. Zhao, A.P.C. Chan, et al., Optimal cooling intervention for construction workers in a hot and humid environment, Build. Environ. 118 (2017) 91–100.
[63] M. Itani, N. Ghaddar, K. Ghali, et al., Experimental study on effective placement of PCM packets in cooling vest to improve performance in warm environment, in: Heat Transfer Summer Conference. Vol. 57885. American Society of Mechanical Engineers, vol. 57885, 2017 V001T04A002.
[64] R. Karkalić, D.B. Jovanović, S.S. Radaković, et al., The influence of the passive evaporative cooling vest on a chemical industry workers and physiological strain level in hot conditions, Hem. Ind. 69 (6) (2015) 587–594.
[65] J.K.W. Lee, A.C.H. Koh, S.X.T. Koh, et al., Neck cooling and cognitive performance following exercise-induced hyperthermia, Eur. J. Appl. Physiol. 114 (2014) 375–384.
[66] M.J. Luomala, J. Oksa, J.A. Salmi, et al., Adding a cooling vest during cycling improves performance in warm and humid conditions, J. Therm. Biol. 37 (1) (2012) 47–55.
[67] C. Gao, K. Kuklane, I. Holmér, Cooling vests with phase change materials: the effects of melting temperature on heat strain alleviation in an extremely hot environment, Eur. J. Appl. Physiol. 111 (2011) 1207–1216.
[68] C.J. Tyler, C. Sunderland, Cooling the neck region during exercise in the heat, J. Athl. Train. 46 (1) (2011) 61–68.
[69] D. Barr, W. Gregson, L. Sutton, et al., A practical cooling strategy for reducing the physiological strain associated with firefighting activity in the heat, Ergonomics 52 (4) (2009) 413–420.
[70] R.M. Lopez, M.A. Cleary, L.C. Jones, et al., Thermoregulatory influence of a cooling vest on hyperthermic athletes, J. Athl. Train. 43 (1) (2008) 55–61.
[71] C. Chou, Y. Tochihara, T. Kim, Physiological and subjective responses to cooling devices on firefighting protective clothing, Eur. J. Appl. Physiol. 104 (2008) 369–374.
[72] A.P.C. Chan, Y. Yang, F.K.W. Wong, et al., Reduction of physiological strain under a hot and humid environment by a hybrid cooling vest, J. Strength Condit Res. 33 (5) (2019) 1429–1436.
[73] Y. Guo, A.P.C. Chan, F.K.W. Wong, et al., Developing a hybrid cooling vest for combating heat stress in the construction industry, Textil. Res. J. 89 (3) (2019) 254–269.
[74] W. Song, F. Wang, The hybrid personal cooling system (PCS) could effectively reduce the heat strain while exercising in a hot and moderate humid environment, Ergonomics 59 (8) (2016) 1009–1018.
[75] Y. Zhang, P.A. Bishop, J.M. Green, et al., Evaluation of a carbon dioxide personal cooling device for workers in hot environments, J. Occup. Environ. Hyg. 7 (7) (2010) 389–396.
[76] B.S. Cadarette, L. Levine, J.E. Staab, et al., Upper body cooling during exercise-heat stress wearing the improved toxicological agent protective system for HAZMAT operations, AIHA J. 64 (4) (2003) 510–515.
[77] H. Yang, B. Cao, Y. Ju, et al., The effects of local cooling at different torso parts in improving body thermal comfort in hot indoor environments, Energy Build. 198 (2019) 528–541.
[78] H. Pallubinsky, L. Schellen, T.A. Rieswijk, et al., Local cooling in a warm environment, Energy Build. 113 (2016) 15–22.
[79] Y. Ke, F. Wang, P. Xu, et al., On the use of a novel nanoporous polyethylene (nanoPE) passive cooling material for personal thermal comfort management under uniform indoor environments, Build. Environ. 145 (2018) 85–95.
[80] T. Katsuura, K. Tomioka, H. Harada, et al., Effects of cooling portions of the head on human thermoregulatory response, J. Physiol. Anthropol. 15 (2) (1996) 67–74.
[81] A.L. Vallerand, R.D. Michas, B.E.J. Frim, et al., Heat balance of subjects wearing protective clothing with a liquid- or air-cooled vest, Aviat Space Environ. Med. 62 (1991) 383–391.
[82] L.V. Hedges, I. Olkin, Statistical Methods for Meta-Analysis, Academic press, 2014.
[83] W.G. Melsen, M.C.J. Bootsma, M.M. Rovers, et al., The effects of clinical and statistical heterogeneity on the predictive values of results from meta-analyses, Clin. Microbiol. Infect. 20 (2) (2014) 123–129.
[84] P. Sdgwick, Meta-analyses: heterogeneity and subgroup analysis, BMJ 346 (2013) f4040.
[85] C.C.W.G. Bongers, M.T.E. Hopman, T.M.H. Eijsvogels, Cooling interventions for athletes: an overview of effectiveness, physiological mechanisms, and practical considerations, Temperature 4 (1) (2017) 60–78.
[86] S.B. Alhadad, I.C.C. Low, J.K.W. Lee, Thermoregulatory responses to ice slurry ingestion during low and moderate intensity exercises with restrictive heat loss, J. Sci. Med. Sport 24 (2021) 105–109.
[87] C.J. Tyler, C. Sunderland, S.S. Cheung, The effect of cooling prior to and during exercise on exercise performance and capacity in the heat: a meta-analysis, Br. J. Sports Med. 49 (1) (2015) 7–13.
[88] T. Maroni, B. Dawson, G. Landers, et al., Hand and torso pre-cooling does not enhance subsequent high-intensity cycling or cognitive performance in heat, Temperature 7 (2) (2020) 165–177.
[89] C.J. Tyler, P. Wild, C. Sunderland, Practical neck cooling and time-trial running performance in a hot environment, Eur. J. Appl. Physiol. 110 (5) (2010) 1063–1074.
[90] C.J. Tyler, C. Sunderland, Neck cooling and running performance in the heat: single versus repeated application, Med. Sci. Sports Exerc. 43 (12) (2011) 2388–2395.
[91] T.M. McLellan, J. Frim, D.G. Bell, Efficacy of air and liquid cooling during light and heavy exercise while wearing NBC clothing, Aviat Space Environ. Med. 70 (8) (1999) 802–811.
[92] M. Wegmann, O. Faude, W. Poppendieck, et al., Pre-cooling and sports performance: a meta-analytical review, Sports Med. 42 (2012) 545–564.
[93] D.J. Hornery, S. Papalia, I. Mujika, et al., Physiological and performance benefits of halftime cooling, J. Sci. Med. Sport 8 (1) (2005) 15–25.
[94] R. Leung, A.N. Lee, H. Zeng, et al., An assessment of a rating of perceived exertion scale for exercise intensity reproduction. Research quarterly for exercise and sport. 2-4 park square, milton park, abingdon OX14 4RN, oxon, england, Routledge Journals, Taylor & Francis Ltd 79 (1) (2008) A39–A40.
[95] B. Larsen, K. Netto, B. Aisbett, The effect of body armor on performance, thermal stress, and exertion: a critical review, Mil. Med. 176 (11) (2011) 1265–1273.
[96] J.H. Kim, A. Coca, W.J. Williams, et al., Subjective perceptions and ergonomics evaluation of a liquid cooled garment worn under protective ensemble during an intermittent treadmill exercise, Ergonomics 54 (7) (2011) 626–635.
[97] X. Xu, J. Gonzalez, Determination of the cooling capacity for body ventilation system, Eur. J. Appl. Physiol. 111 (2011) 3155–3160.
[98] J.M. Ding, W.R. Zhao, W.L. Jin, et al., Advanced thermoelectric materials for flexible cooling application, Adv. Funct. Mater. 31 (2021) 2010695.