Sports Medicine (2024) 54:447–471
https://doi.org/10.1007/s40279-023-01940-y

SYSTEMATIC REVIEW

Performance Benefits of Pre- and Per-cooling on Self-paced Versus Constant Workload Exercise: A Systematic Review and Meta-analysis

Tessa M. van de Kerkhof[1] · Coen C. W. G. Bongers[1,2] · Julien D. Périard[3] · Thijs M. H. Eijsvogels[1]

Accepted: 17 September 2023 / Published online: 6 October 2023

Abstract

Background and Objective Exercise in hot environments impairs endurance performance. Cooling interventions can attenuate the impact of heat stress on performance, but the influence of an exercise protocol on the magnitude of performance benefit remains unknown. This meta-analytical review compared the effects of pre- and per-cooling interventions on performance during self-paced and constant workload exercise in the heat.

Methods The study protocol was preregistered at the Open Science Framework (https://osf.io/wqjb3). A systematic literature search was performed in PubMed, Web of Science, and MEDLINE from inception to 9 June, 2023. We included studies that examined the effects of pre- or per-cooling on exercise performance in male individuals under heat stress (> 30 °C) during self-paced or constant workload exercise in cross-over design studies. Risk of bias was assessed using the Cochrane Risk of Bias Tool for randomized trials.

Results Fifty-nine studies ($n=563$ athletes) were identified from 3300 records, of which 40 ($n=370$ athletes) used a self-paced protocol and 19 ($n=193$ athletes) used a constant workload protocol. Eighteen studies compared multiple cooling interventions and were included more than once (total $n=86$ experiments and $n=832$ paired measurements). Sixty-seven experiments used a pre-cooling intervention and 19 used a per-cooling intervention. Average ambient conditions were 34.0 °C [32.3–35.0 °C] and 50.0% [40.0–55.3%] relative humidity. Cooling interventions attenuated the performance decline in hot conditions and were more effective during a constant workload (effect size [ES] = 0.62, 95% confidence interval [CI] 0.44–0.81) compared with self-paced exercise (ES = 0.30, 95% CI 0.18–0.42, $p=0.004$). A difference in performance outcomes between protocols was only observed with pre-cooling (ES = 0.74, 95% CI 0.50–0.98 vs ES = 0.29, 95% CI 0.17–0.42, $p=0.001$), but not per-cooling (ES = 0.45, 95% CI 0.16–0.74 vs ES = 0.35, 95% CI 0.01–0.70, $p=0.68$).

Conclusions Cooling interventions attenuated the decline in performance during exercise in the heat, but the magnitude of the effect is dependent on exercise protocol (self-paced vs constant workload) and cooling type (pre- vs per-cooling). Pre-cooling appears to be more effective in attenuating the decline in exercise performance during a constant workload compared with self-paced exercise protocols, whereas no differences were found in the effectiveness of per-cooling.

✉ Thijs M. H. Eijsvogels
Thijs.Eijsvogels@radboudumc.nl

[1] Department of Physiology (392), Radboud University Medical Center, Radboud Institute for Health Sciences, P.O. Box 9101, 6500 HB Nijmegen, The Netherlands

[2] School of Sports and Exercise, HAN University of Applied Sciences, Nijmegen, The Netherlands

[3] University of Canberra Research Institute for Sport and Exercise, Canberra, ACT, Australia

Key Points

Pre-cooling is more effective in constant workload exercise compared with self-paced exercise in the heat.

Per-cooling provides comparable benefits for constant and self-paced exercise in the heat.

Substantial differences in the magnitude of performance benefits across different types of cooling interventions were observed, which emphasizes the need for more research to determine the most effective type of cooling under specific exercise conditions (e.g., type, duration).

1 Introduction

Exercise in the heat results in internal heat storage, impairment of athletic performance [1], and an increased risk for heat-related illness [2, 3]. Heat mitigation strategies, such as cooling interventions and heat acclimation, have been shown to attenuate the development of thermal strain and improve exercise performance in the heat [4, 5]. Heat acclimation is regarded as the primary intervention to undertake prior to exercise in the heat [1], but requires a dedicated time frame to induce physiological adaptations. In contrast, cooling interventions can provide an immediate reduction in thermal strain by increasing heat storage capacity directly prior to exercise (pre-cooling) or attenuating the increase in core temperature during exercise (per-cooling). Cooling interventions can be applied externally (i.e., cooling garments, cold water immersion, or fanning) and internally (i.e., cold fluid or ice ingestion). Over the past decade, several reviews and meta-analyses have demonstrated that both pre-cooling and per-cooling can effectively attenuate the decline in exercise performance in the heat [6–9]. However, a limitation of previous work is that all available evidence was pooled and the type of exercise protocol (i.e., self-paced and constant workload exercise) was not factored in when evaluating the performance benefits of cooling. This may have led to over- or under-estimation of the cooling-induced performance benefits as the pooled outcomes may not be representative of exercise in a sport-specific setting (e.g., marathon running, individual time trial cycling, team sports).

Endurance performance can be assessed in laboratory settings using different protocols. The objective of self-paced exercise protocols is to complete a known distance or amount of work as quickly as possible, or maintain the highest workload for a given time, with the ability to adjust the workload based on maintaining an optimal performance intensity [1]. In contrast, constant workload protocols adopt a set work rate and individual pacing cannot occur beyond adjusting cadence or ceasing exercise. These are typically used to isolate independent variables (e.g., cooling intervention) in a well-controlled environment to examine their effect on dependent variables (e.g., volitional fatigue). Although both types of exercise protocols can reliably assess changes in exercise performance (i.e., sensitivity) [10, 11] and have external validity (i.e., representative for race conditions), the magnitude of performance change may differ markedly, with changes in time to volitional fatigue stemming from an acute intervention (e.g., heat or hypoxia) typically being much larger than those of self-paced exercise [10, 12, 13].

The aim of this systematic review and meta-analysis was to compare the effects of cooling interventions on performance outcomes during self-paced and constant workload exercise in the heat by standardizing the impact of cooling on performance and presenting effect sizes (ESs). Second, we evaluated the impact of the type of cooling (i.e., pre-cooling vs per-cooling) on exercise performance between exercise protocols. We hypothesized that cooling strategies would be equally effective between self-paced and constant workload exercise.

2 Methods

2.1 Search Strategy

This review was performed according to the Preferred Items for Systematic Reviews and Meta-Analysis—Protocol (PRISMA-P) statement [14] and was pre-registered with the Open Science Framework Registries (https://osf.io/wqjb3). A systematic literature search was conducted in PubMed, Web of Science, and MEDLINE. Three main search themes were used, which included exercise, cooling interventions, and an exercise performance outcome measure. Titles and abstracts were searched in addition to using Medical Subject Heading terms in PubMed. Words within the themes were combined using the Boolean operator "OR", while the three themes were connected by "AND" (Table 1 of the Electronic Supplementary Material [ESM]). The final search was performed from inception up to 9 June, 2023. Search results from these databases were combined and duplicates removed using Mendeley Reference Management Software (Elsevier, London, UK). Two reviewers (T.M.K and C.C.W.G.B) screened the article titles and abstracts for inclusion; in the case of disagreement between those reviewers, a third reviewer (T.M.H.E) was consulted and decided on inclusion or exclusion. The reference list of included articles was screened for any additional articles that were missed by the literature search.

2.2 Inclusion Criteria

Studies were included if they (1) applied a pre-cooling or a per-cooling strategy and adopted a crossover design; (2) used a self-paced or a constant workload exercise protocol; (3) were performed in hot ambient conditions (≥ 30 °C); (4) included data reported separately for male and female individuals; and (5) reported at least one outcome parameter related to exercise performance. Studies were excluded if they (1) adopted a combination of pre- and per-cooling interventions and (2) were scored with a high risk of bias [15].

2.3 Study Classification

All included studies were classified into two groups based on the exercise protocol: self-paced or constant workload exercise. Self-paced exercise protocols were defined as exercise protocols that consisted of a fixed distance, time, or work to be completed and allowed participants to change the speed or workload during the trial. Constant workload protocols were defined as exercise protocols that were performed at a workload equivalent to a percent of maximal aerobic power (e.g., 60% of maximal oxygen consumption [VO_{2max}]) or peak workload (e.g., 70% of peak power output), or a specified rating of perceived exertion (RPE) (e.g., RPE of 15) until volitional fatigue/exhaustion. Studies adopting a warm-up and those where a pre-loaded exercise trial was performed at a different exercise protocol than the actual performance trial were classified based on the characteristics of the performance trial. For example, if a pre-loaded constant workload trial preceded a self-paced exercise trial, only the data from the self-paced trial were included in the meta-analysis.

Pre-cooling was defined as any cooling intervention applied either prior to the performance trial (i.e., at rest, warm-up, or pre-loaded trial) or during exercise breaks (e.g., 15-min half-time break). If cooling was applied both prior to the trial and during the half-time break, all data from the performance trial were used. However, if cooling was only applied during half-time, data from the second half were extracted, given that the first half was similar in both the control and intervention trials (i.e., randomized design and comparable environmental conditions). Per-cooling was defined as any cooling intervention that was applied during exercise as part of the performance trial. Studies that investigated more than one cooling intervention in separate trials were included more than once. Studies adopting multiple cooling interventions at the same time (e.g., cooling vest and cold/ice water ingestion) were classified as mixed-method cooling. We did not distinguish between or exclude non-thermal cooling methods as it has been shown to improve exercise performance [16]. We therefore also included menthol-based cooling interventions in our systematic review and meta-analysis.

2.4 Risk of Bias Analysis

Risk of bias was assessed independently by two researchers (T.M.K and C.C.W.G.B) according to the Cochrane Risk of Bias Tool for randomized trials to assess the methodological quality of the included studies. After the initial assessment, the risk of bias of both researchers was compared and in cases where a consensus was not reached, the evaluation of a third researcher (T.M.H.E) was decisive.

2.5 Data Extraction

Data were extracted from each study to a predefined Excel sheet (Microsoft Excel, version 16.73). This included: (1) article information (author name, year, title, study design); (2) participant characteristics (age, sex, and VO_{2max}); (3) study characteristics (number of participants, ambient conditions [ambient temperature, relative humidity, and air flow], exercise characteristics [running, cycling], exercise protocol, exercise duration, type of cooling intervention, timing of cooling,); and (4) exercise performance data (mean ± standard deviation). For self-paced exercise, relevant outcome parameters included finish time (in seconds), total distance covered (in meters), mean power output (in Watts), total work done (in kilojoules), or peak power output (in Watts). A single measure was selected when multiple power output outcome measures were reported, prioritized as mean power output, total work done, and peak power output. For constant workload exercise, outcome measures included time to exhaustion (in seconds), mean power output (in Watts), total work done (in kilojoules), or peak power output (in Watts). A single measure was selected when multiple power output outcome measures were reported, prioritized as mean power output, total work done and peak power output. In the case of missing data, only the available data were analyzed and presented. In case data were not explicitly provided in the text, but only in a figure, data were extracted using a validated graphical software program (WebPlotDigitizer version 4.5; Automeris LLC, Pacifica, CA, USA) by a single experienced researcher [17, 18].

2.6 Data Synthesis and Analysis

Data analysis was performed on raw data (means, standard deviation, and sample size) using Review Manager (version 5.4), in line with the Cochrane guidelines. For all included studies, the standardized mean difference was calculated as the Hedges' ES (ES = difference in outcome between conditions/standard deviation of outcome among participants) with a corresponding 95% confidence interval (CI) [19]. The magnitude of Hedges' g was interpreted as: < 0.2, trivial; 0.2–0.49, small effect; 0.5–0.79, moderate effect; ≥ 0.8, large effect [20]. Heterogeneity was assessed using I^2 statistics with < 25% being considered low heterogeneity and > 75% high heterogeneity [21]. A fixed-effects model was used to calculate the pooled weighted average ES to correct for differences in the sample size between studies by using the inverse-variance weighted average method [22]. Stratified analyses were also performed to compare the effect of cooling type (pre- vs per-cooling) between self-paced and constant workload exercise protocols. Exploratory analyses were additionally performed to assess the impact of exercise duration on the ES. Potential publication bias was assessed by visual inspection of funnel plot asymmetry. All data were presented as mean ± standard deviation. To assess between-study normality of data, a Kolmogorov–Smirnov test was performed; in the case of non-normality, the median with interquartile range was reported. The significance level for all statistical tests was set at $p < 0.05$. Data analyses on the ESs were conducted using Review Manager, whereas publication bias was assessed using Rstudio (version 1.4.1106; packages: tidyverse, meta, metafor).

3 Results

3.1 Participants and Included Studies

The literature search identified 3300 articles after the removal of duplicates. After the initial title and abstract screening and subsequent full-text screening, 61 studies complied with our inclusion criteria, of which two [23, 24] were excluded owing to a high risk of bias because of missing data (Fig. 1). In total, 59 studies ($n = 563$ athletes, age: 24.0 [21.0–26.0] years, VO_{2peak}: 55.8 ± 6.0 mL kg^{-1} min^{-1}) were included in the meta-analysis, of which 40 studies ($n = 370$ athletes) comprised a self-paced exercise protocol [25–64] (Table 1) and 19 studies ($n = 193$ athletes) comprised a constant workload protocol [65–83] (Table 2). A total of 18 studies compared multiple cooling interventions and were therefore included more than once. This resulted in 86 experiments ($n = 832$ paired measurements) in which exercise performance was compared between the control and cooling conditions. Almost all studies were conducted in an indoor laboratory setting ($n = 56$; 95%). Average ambient conditions were 34.0 °C [32.3–35.0 °C] and 50.0% [40.0–55.3%] relative humidity and did not differ between self-paced and constant workload studies ($p = 0.11$ and $p = 0.49$, respectively). Furthermore, 22 out of 59 studies (37%) reported information on airflow, which was 2.1 ± 1.5 m s^{-1} on average and did not differ between study protocols ($p = 0.40$).

3.2 Risk of Bias Analysis

A few outliers and little asymmetry were observed in the funnel plots for the self-paced and constant workload exercise protocol studies (Fig. 2). The risk of bias analysis revealed that 98% of included studies had "some concerns" (Tables 3, 4). This mainly related to missing information on the concealment of the allocation sequence until participants were assigned to an intervention (i.e., Domain 1) as well as missing information on whether a pre-specified analysis plan was used or not (i.e., Domain 5). The risk of bias was comparable between the self-paced and constant workload exercise protocol studies.

3.3 Self-Paced Exercise Studies

Fifty-nine experiments (exercise duration: 40.0 [27.0–60.0] minutes) were available for self-paced exercise performance analysis, of which 51 used a pre-cooling intervention and eight used a per-cooling intervention. Mixed-method cooling (25.0%), cooling vests (18.7%), and cold/ice water ingestion (14.9%) were most frequently adopted as cooling strategies (Fig. 1 of the ESM). The median weighted improvement in self-paced exercise performance corresponded to an ES = 0.30, 95% CI 0.18–0.42.

Pre-cooling was applied prior to a time trial (19 out of 51 experiments) or an intermittent sprint protocol (32 out of 51 experiments), whereas per-cooling was predominantly used during a time trial (seven out of eight experiments). The improvement in self-paced exercise performance was similar for pre-cooling (ES = 0.29, 95% CI 0.17–0.42, Fig. 3) and per-cooling (ES = 0.35, 95% CI 0.01–0.70, Fig. 4, $p = 0.74$). We also observed a large variability in the magnitude of the ES across cooling strategies, with no benefits from a cooling collar (ES = 0.00, 95% CI − 0.92 to 0.92) or small benefits from cold water immersion (ES = 0.47, 95% CI 0.15–0.80) for pre-cooling studies (Fig. 3), to large effects using limb cooling (ES = 1.63, 95% CI 0.45–2.81) as a per-cooling intervention (Fig. 4). Finally, no statistical heterogeneity was observed for pre- and per-cooling subgroups ($I^2 = 0\%$, $p = 1.00$ and $I^2 = 0\%$, $p = 0.55$, respectively).

3.4 Constant Workload Exercise Studies

Twenty-seven experiments (exercise duration: 33.6 ± 22.8 min) were available for a constant workload exercise performance analysis, of which 16 experiments used a pre-cooling intervention and 11 experiments used a per-cooling intervention. Cold/ice water ingestion (20.0%), cooling vests

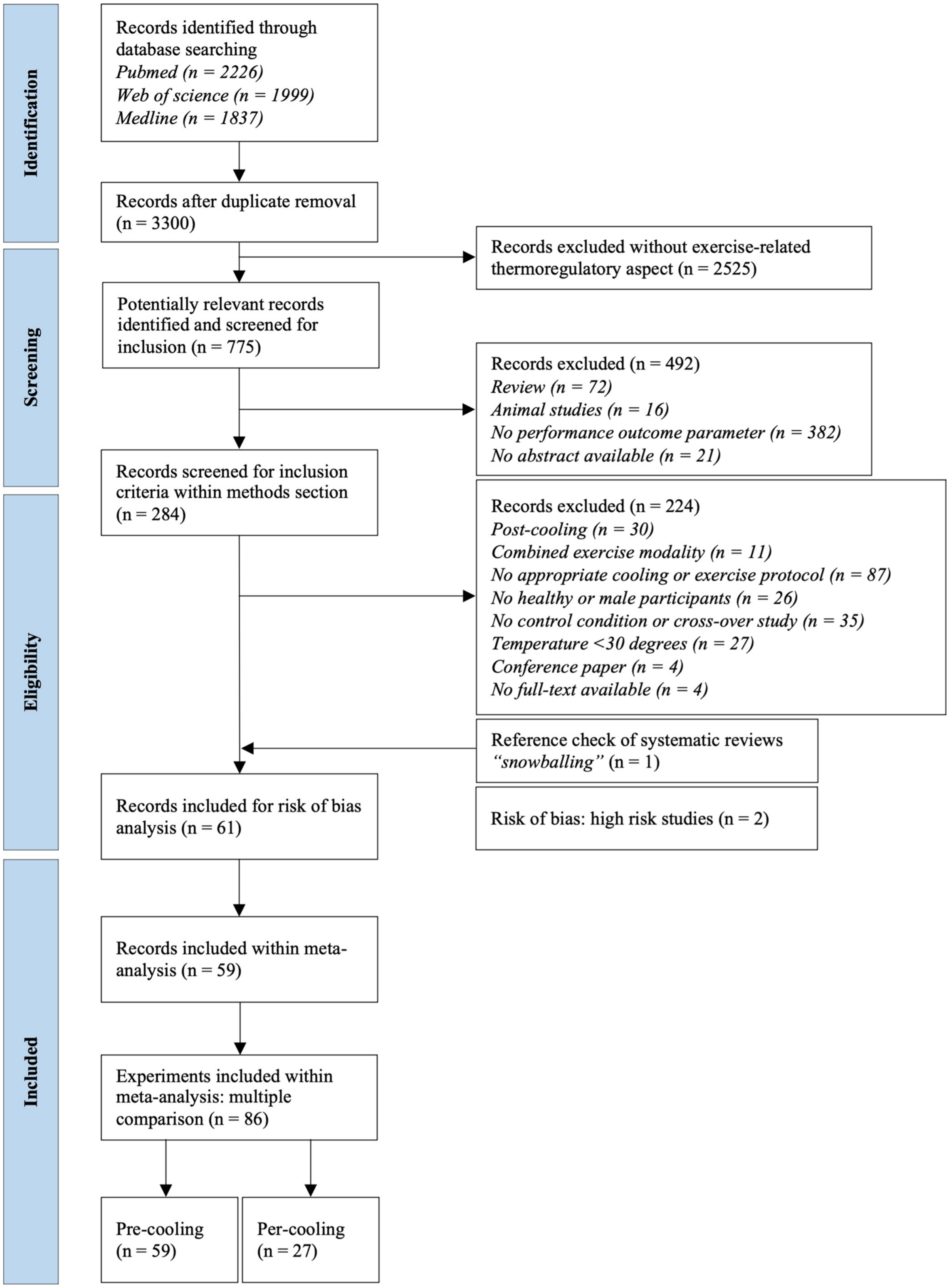


Fig. 1 Flow chart of the systematic search and study selection process

(19.6%), and menthol use (17.7%) were most frequently adopted as cooling strategies (Fig. 1 of the ESM). The median weighted improvement in constant workload exercise performance was ES = 0.62, 95% CI 0.44–0.81. Pre-cooling was applied prior to time to exhaustion (13 out of 16 experiments), an intermittent exercise (1 out of 16 experiments),

Table 1 Study characteristics, self-paced studies

Study	Age (years)	VO_{2max} (mL kg^{-1} min^{-1}) or fitness level	Type of exercise (primary outcome measure)	Type of cooling	Method of cooling	Ambient conditions	Airflow	Lab/field study
Pre-cooling								
Arngrimmson et al. 2004 ($n=9$) [25]	23 ± 4	66.7 ± 5.9	5-km running time trial (time)	Pre-cooling	Cooling vest during warm-up	32 °C/50% RH	Unknown	Lab, indoor
Brade et al. 2014 ($n=12$) [26]	22 ± 2	Team sport players	2 × 30-min repeat sprint cycling, 10-min half-time (mean power output)	Pre-cooling	(a) PCM cooling vest during rest + half-time (b) Ice slushy (7 g/kg BM) during rest; 2.1 g/kg BM during half-time (c) Cooling vest and ice slushy during rest + half-time	35 °C/60% RH	Unknown	Lab, indoor
Byrne et al. 2011 ($n=7$) [37]	21 ± 2	Recreational cyclists	30-min cycling time trial (total distance covered)	Pre-cooling	Cold water ingestion (2 °C, 900 mL) during rest	32 °C/60% RH	3.2 m/s (fan)	Lab, indoor
Castle et al. 2006 ($n=12$) [48]	23 ± 1	47.3 ± 2.4	20 × 2-min intermittent cycling sprint protocol (total work done)	Pre-cooling	(a) Cooling vest (10.7 °C) during rest (b) Cold water immersion (17.8 °C) during rest (c) Cooling packs (− 16.0 °C) during rest	33.7 °C/51.6% RH	Unknown	Lab, indoor
Chaen et al. 2019 ($n=8$) [59]	21 ± 2	Well trained	2 × 30-min intermittent cycling protocol, 15-min half-time (mean power output)	Pre-cooling	Cooling vest (− 1 °C) during half-time	33 °C/50% RH	Unknown	Lab, indoor
Coelho et al. 2021 ($n=15$) [60]	23 ± 4	42.3 ± 4.4	5-km running time trial (time)	Pre-cooling	Head cooling (− 20.2 °C) during rest	35 °C/50% RH	1.5 m/s	Lab, indoor
Duffield et al. 2003 ($n=7$) [61]	20 ± 2	Well trained	4 × 15-min intermittent cycling sprint protocol, 10-min half-time (mean power output)	Pre-cooling	Cooling vest during rest + each break	30 °C/60% RH	Unknown	Lab, indoor
Duffield et al. 2007 ($n=9$) [62]	21 ± 1	Well trained	2 × 30-min intermittent running sprint protocol, 10-min half-time (total distance covered)	Pre-cooling	(a) Cold water immersion (14 °C) during rest and cooling vest during warm-up + half-time (b) Cooling vest during rest + warm-up + half-time	32 °C/30% RH	Unknown	Lab, indoor

Table 1 (continued)

Study	Age (years)	VO_{2max} (mL kg^{-1} min^{-1}) or fitness level	Type of exercise (primary outcome measure)	Type of cooling	Method of cooling	Ambient conditions	Airflow	Lab/field study
Duffield et al. 2009 (*n* = 7) [63]	20 ± 1	Well trained	4 × 5-min intermittent running sprint protocol, 10-min half-time (total distance covered)	Pre-cooling	Cooling vest and cooling packs during rest	32.4 °C/44.0% RH	Unknown	Lab, indoor
Duffield et al. 2010 (*n* = 8) [64]	25 ± 3	Well trained	40-min cycling time trial (mean power output)	Pre-cooling	Cold water immersion (14 °C) during rest	33 °C/50% RH	No additional airflow	Lab, indoor
Duffield et al. 2013 (*n* = 9) [27]	23 ± 3	Well trained	2 × 10-min intermittent running and 6 × 3-min small-sided games, 5-min recovery (total distance covered)	Pre-cooling	Cooling vest during rest + half-time and cold towel (5 °C) during rest + half-time and ice slurry ingestion (350 mL) during rest	30 °C/75% RH	Unknown	Field, outdoor
Faulkner et al. 2015 (*n* = 10) [28]	25 ± 6	61.3 ± 4.3	75% W_{max} cycling time trial (time)	Pre-cooling	(a) Evaporative and conductive cooling vest (COLD) during rest (b) Evaporative cooling vest (COOL; 14.3 °C) during rest	35.0 °C/50.6% RH	Unknown	Lab, indoor
Faulkner et al. 2019 (*n* = 8) [29]	25 ± 6	61.3 ± 4.3	75% W_{max} cycling time trial (time)	Pre-cooling	Evaporative and conductive cooling vest (COLD) during rest	35.0 °C/50.6% RH	3 m/s (fan)	Lab, indoor
Fiol et al. 2021 (*n* = 12) [30]	26 ± 4	57.6 ± 7.9	5-km cycling time trial (time)	Pre-cooling	(a) Low-dose cold air inhalation (60 s on; 4 min off) during preloaded trial (b) High-dose cold air inhalation (60 s on; 60 s off) during preloaded trial	30 °C/55% RH	3.5 m/s (fan)	Lab, indoor
Gerrett et al. 2017 (*n* = 12) [31]	30 ± 3	58.5 ± 8.1	31-min intermittent running protocol (total distance covered)	Pre-cooling	Ice slurry ingestion (7.5 g/kg; 0.14 °C) during rest	30.2 °C/42.5% RH	1.3 m/s (fan)	Lab, indoor
Ihsan et al. 2010 (*n* = 7) [32]	28 ± 3	Trained	40-km cycling time trial (time)	Pre-cooling	Ice slurry ingestion (6.8 g/kg BM; 1.4 °C) during rest	30 °C/75% RH	Unknown	Lab, indoor
Katica et al. 2018 (*n* = 8) [33]	25 ± 3	50.2 ± 7.2	16.1-km cycling time trial (time)	Pre-cooling	Cooling vest during warm-up	35.0 °C/43.8% RH	3.3 m/s	Lab, indoor

Table 1 (continued)

Study	Age (years)	VO_{2max} (mL kg^{-1} min^{-1}) or fitness level	Type of exercise (primary outcome measure)	Type of cooling	Method of cooling	Ambient conditions	Airflow	Lab/field study
Kay et al. 1999 (n = 8) [34]	24 ± 2	64.5 ± 3.3	30-min cycling time trial (total distance covered)	Pre-cooling	Cold water immersion (8–11 °C) during rest	31.4 °C/60.2% RH	Unknown	Lab, indoor
Maia-Lima et al. 2017 (n = 8) [35]	28 ± 3	55.7 ± 7.9	30-km cycling time trial (time)	Pre-cooling	Cold water immersion (24 °C) during rest	35 °C/68% RH	0.5 m/s (fan)	Lab, indoor
Maroni et al. 2018 (n = 12) [36]	21 ± 2	Trained	2 × 30-min repeat sprint cycling protocol, 10-min half-time (mean power output)	Pre-cooling	(a) Cooling glove (~ 16 °C) during half-time (b) Cooling jacket (0–2 °C) during half-time (c) Cooling glove (~ 16 °C) and cooling jacket (0–2 °C) during half-time	35.0 °C/52.5% RH	No active airflow	Lab, indoor
Maroni et al. 2020 (n = 10) [38]	21 ± 3	65.7 ± 10.7	6 × 15-s cycling sprint with varying recovery times + 2 × 5-min time trial (mean power output)	Pre-cooling	(a) Cooling glove during rest + warm-up (b) Cooling jacket (0–2 °C) during rest + warm-up (c) Cooling glove and cooling jacket (0–2 °C) during rest + warm-up	35.0 °C/56.6% RH	Unknown	Lab, indoor
Mazalan et al. 2022 (n = 9) [39]	28 ± 3	Trained	30-min intermittent cycling sprint protocol (total work done)	Pre-cooling	Ice slurry ingestion (7 g/kg; − 0.4 °C)	35.0 °C/70% RH	Unknown	Lab, indoor
Minett et al. 2011 (n = 10) [40]	21 ± 3	Well trained	2 × 35-min intermittent running sprint protocol (total distance covered)	Pre-cooling	(a) Head cooling (5.0 °C) during rest + half-time (b) Head cooling (5.0 °C) and hand immersion (9.0 °C) during rest + half-time (c) Mixed-method whole body cooling (head cooling and hand immersion and cooling vest and cooling packs) during rest + half-time	33.0 °C/33.3% RH	Unknown	Lab, indoor

Table 1 (continued)

Study	Age (years)	VO_{2max} (mL kg^{-1} min^{-1}) or fitness level	Type of exercise (primary outcome measure)	Type of cooling	Method of cooling	Ambient conditions	Airflow	Lab/field study
Minett et al. 2012a (n = 10) [41]	23 ± 8	Well trained	45-min 6-over bowling spell	Precooling	Wet towel (5.0 °C) on head, neck, and shoulders and cooling vest (− 20 °C) and wrist immersion (9.0 °C) and cooling packs (− 20 °C) on legs during rest	31.9 °C/63.5% RH	Unknown	Field, outdoor
Minett et al. 2012b (n = 8) [42]	22 ± 3	Well trained	2 × 35-min intermittent running protocol (total distance covered)	Pre-cooling	Head cooling (5.0 °C) and hand immersion (9.0 °C) and cooling vest and cooling packs during rest + half-time	33.0 °C/33.9% RH	Unknown	Lab, indoor
Moss et al. 2021 (n = 9) [43]	32 ± 10	65 ± 7	15-min cycling time trial (total distance covered)	Pre-cooling	(a) Cold water immersion (22–24 °C) and cold water ingestion (1.25 mL/kg; ~ 10 °C) during rest (b) Cooling collar during pre-loaded trial (c) Cold water immersion (22–24 °C) and cold water ingestion (1.25 mL/kg; ~ 10 °C) during rest and cooling collar during pre-loaded trial	40 °C/50% RH	1.5 m/s	Lab, indoor
Naito et al. 2020 (n = 7) [44]	31 ± 4	Physically active	30 × 1-min sprint cycling protocol (mean power output)	Pre-cooling	Ice slurry ingestion (1.25 mL/kg BM; − 1 °C) during each break and half-time	36.5 °C/50% RH	Unknown	Lab, indoor
Skein et al. 2012 (n = 10) [45]	20 ± 1	Physically active	50-min intermittent running protocol (total distance covered)	Pre-cooling	Cold water immersion (10 °C) during rest	31 °C/33% RH	Unknown	Lab, indoor
Stevens et al. 2016 (n = 11) [46]	29 ± 9	Moderately trained	5-km running time trial (time)	Pre-cooling	Ice slurry ingestion (7.5 g/kg BM; − 1 °C) during rest	33 °C/46% RH	4 m/s (fan)	Lab, indoor

Table 1 (continued)

Study	Age (years)	VO_{2max} (mL kg^{-1} min^{-1}) or fitness level	Type of exercise (primary outcome measure)	Type of cooling	Method of cooling	Ambient conditions	Airflow	Lab/field study
Stevens et al. 2017a (n = 11) [47]	30 ± 9	61 ± 6	3-km running time trial (time)	Pre-cooling	Cold water immersion (23–24 °C) and ice slurry ingestion (7.5 g/kg BM) during rest	32.5 °C/46.8% RH	4 m/s (fan)	Lab, indoor
Stevens et al. 2017b (n = 9) [49]	30 ± 12	Trained	5-km running time trial (time)	Pre-cooling	Cold water immersion (23–24 °C) during rest	33 °C/34% RH	4 m/s (fan)	Lab, indoor
Thomas et al. 2019 (n = 10) [50]	31 ± 6	56.2 ± 6.6	46-min intermittent running protocol (total distance covered)	Pre-cooling	(a) Ice slurry ingestion (7.5 g/kg BM; – 0.5 °C) during rest (b) Cooling vest (23.4 °C during rest (c) Ice slurry ingestion (7.5 g/kg BM; – 0.5 °C) and cooling vest (23.4 °C) during rest	34.4 °C/36.3% RH	1.3 m/s (fan)	Lab, indoor
Yanaoka et al. 2022 (n = 9) [51]	21 ± 2	57.2 ± 5.4	5-min cycling time trial	Pre-cooling	Ice slurry ingestion (5.0 g/kg; – 1.3 °C) and cooling vest during 15-min break	35 °C/50% RH	No additional airflow	Lab, indoor
Zhang et al. 2022 (n = 11) [52]	21 ± 2	Physciall active	Yo-Yo intermittent running protocol (total distance covered)	Pre-cooling	(a) Lower limb cold water immersion (15 °C) during 15-min break (b) Whole body cold water immersion (15 °C) during 15-min break	39.7 °C/unknown	Unknown	Field, outdoor
Per-cooling								
Barwood et al. 2015 (n = 8) [53]	21 ± 2	Physically active	16.1-km cycling time trial (time)	Per-cooling	Menthol spray (100 mL) at 10th km of time trial	33.5 °C/33% RH	2.25 m/s (fan)	Lab, indoor
Carvalho et al. 2014 (n = 10) [54]	25 ± 1	67.2 ± 1.8	40-km cycling time trial (time)	Per-cooling	Cold water ingestion (10 °C) during time trial	35 °C/60% RH	0.5 m/s	Lab, indoor
Hsu et al. 2005 (n = 8) [55]	27 ± 2	54.1 ± 3.1	30-km cycling time trial (time)	Per-cooling	Hand cooling (22 °C) during time trial	31.9 °C/24% RH	No additional airflow	Lab, indoor

Table 1 (continued)

Study	Age (years)	VO_{2max} (mL kg^{-1} min^{-1}) or fitness level	Type of exercise (primary outcome measure)	Type of cooling	Method of cooling	Ambient conditions	Airflow	Lab/field study
Minniti et al. 2011 (n=8) [56]	25±5	53.7±4.7	15-min running time trial (total distance covered)	Per-cooling	Neck cooling collar during preloaded trial + time trial	30.4 °C/53% RH	Unknown	Lab, indoor
Stevens et al. 2016 (n=11) [46]	29±9	Moderately trained	5-km running time trial (time)	Per-cooling	Menthol swilling (25 mL; 22 °C) at the 0.2-km mark of every 1 km	33 °C/46% RH	4 m/s (fan)	Lab, indoor
Stevens et al. 2017b (n=9) [49]	30±12	Trained	5-km running time trial (time)	Per-cooling	Facial water spray (3 sprays; 22 °C) at the 0.2-km mark of every 1 km	33 °C/34% RH	4 m/s (fan)	Lab, indoor
Sunderland et al. 2015 (n=7) [57]	26±3	53.5±2.7	5×6-s sprints and 2×45-min football specific intermittent protocol (mean power output), 15-min half-time	Per-cooling	Neck cooling collar during whole trial	33.0 °C/53% RH	Unknown	Lab, indoor
Tyler et al. 2010 (n=8) [58]	25±3	54.9±3.1	15-min time trial (total distance covered)	Per-cooling	Neck cooling collar during whole trial	30.4 °C/53% RH	Unknown	Lab, indoor

BM body mass, *lab* laboratory, *min* minutes, *PCM* phase change material, *RH* relative humidity, *sec* seconds, VO_{2max} maximal oxygen consumption, W_{max} maximal workload

Table 2 Study characteristics, constant workload studies

Study	Age (years)	VO_{2max} (mL kg^{-1} min^{-1}) or fitness level	Type of exercise (primary outcome measure)	Type of cooling	Method of cooling	Ambient conditions	Airflow	Lab/field study
Pre-cooling								
Barwood et al. 2019 (*n* = 8) [65]	22 ± 2	Trained	Cycling test to exhaustion at 70% P_{max}, (time to exhaustion)	Pre-cooling	Menthol spray (100 mL) during pre-loaded trial	35 °C/20% RH	1.85 m/s (fan)	Lab, indoor
Choo et al. 2019 (*n* = 11) [66]	30 ± 6	51.1 ± 8.2	60-min cycling trial at 15 RPE/'hard or heavy' (mean power output)	Pre-cooling	(a) Ice slurry ingestion (1.25 g/kg/5 min; 0.1 °C) during rest (b) Cold water immersion (22.3 °C) during rest	33.9 °C/42.5% RH	Unknown	Lab, indoor
Hasegawa et al. 2005 (*n* = 9) [76]	22 ± 1	48.3 ± 1.7	Cycling test to exhaustion at 80% $VO_{2,max}$ (time to exhaustion)	Pre-cooling	Cooling jacket during pre-loaded trial	32.0 °C/70–80% RH	Unknown	Lab, indoor
Mitchell et al. 2003 (*n* = 11) [77]	24 ± 7	54.8 ± 4.2	Running test to exhaustion at 100% $VO_{2,max}$ (time to exhaustion)	Pre-cooling	Fan cooling with water spray (100 mL/2 min) during rest	38 °C/40% RH	4.0 m/s (fan)	Lab, indoor
Nakamura et al. 2020 (*n* = 8) [78]	22 ± 1	42.4	Cycling text to exhaustion at 75% $VO_{2,max}$ (time to exhaustion)	Pre-cooling	a) Hand and forearm immersion in cold water (10 °C) during rest b) Ice slurry ingestion (4 g/kg BM; – 1 °C) during rest c) Hand and forearm immersion in cold water (10 °C) and ice slurry ingestion (4 g/kg BM; – 1 °C)	35.0 °C/62.5% RH	Unknown	Lab, indoor
Osakabe et al. 2021 (*n* = 8) [79]	23 ± 1	51.8 ± 5.0	2 × 30-min intermittent cycling protocol, 15-min half-time (mean power output)	Pre-cooling	Fan with skin wetting (~ 20 °C) during half-time	35 °C/50% RH	0.8 m/s (fan)	Lab, indoor
Siegel et al. 2012 (*n* = 8) [80]	26 ± 4	54.2 ± 2.5	Running to exhaustion at first ventilatory threshold (time to exhaustion	Pre-cooling	(a) Ice slurry ingestion (7.5 g/kg; – 1 °C) during rest (b) Cold water immersion (24 °C) during rest	34.0 °C/52% RH	Unknown	Lab, indoor
Uckert et al. 2007 (*n* = 20) [81]	26 ± 4	Trained	Running incremental step test to exhaustion (time to exhaustion)	Pre-cooling	Cooling vest (0–5 °C) during rest	30–32 °C/50% RH	Unknown	Lab, indoor
Walters et al. 2017 (*n* = 22) [82]	20 ± 2	Recreationally active	Cycling graded exercise test	Pre-cooling	Cooling cap (5–10 °C) during rest	35 °C/15% RH	Unknown	Lab, indoor

Table 2 (continued)

Study	Age (years)	VO_{2max} (mL kg^{-1} min^{-1}) or fitness level	Type of exercise (primary outcome measure)	Type of cooling	Method of cooling	Ambient conditions	Airflow	Lab/field study
Xu et al. 2021 (*n* = 7) [83]	20 ± 1	60.7 ± 4.1	Running to exhaustion at 80% $VO_{2,max}$ (time to exhaustion)	Pre-cooling	(a) Cooling vest (4 °C) during rest (b) Cold fluid ingestion (2.3 mL/kg BM; 4 °C) during rest (c) Cooling vest (4 °C) and cold fluid ingestion (2.3 mL/kg BM; 4 °C) during rest	38.1 °C/55.3% RH	Unknown	Lab, indoor
Per-cooling								
Cuttel et al. 2016 (*n* = 8) [67]	24 ± 4	Recreationally active	Cycling to exhaustion at 60% W_{max} (time to exhaustion)	Per-cooling	(a) Cooling vest (stored at − 24 °C) during whole trial (b) Neck cooling collar (stored at − 24 °C) during time trial	35 °C/50.1% RH	Unknown	Lab, indoor
Flood et al. 2017 (*n* = 8) [68]	26 ± 5	55.4 ± 6.0	Cycling to exhaustion at 16 RPE/'hard or very hard' (time to exhaustion)	Per-cooling	Menthol mouth rinse (25 mL every 10 min; 19.8 °C) during whole trial	35.0 °C/47.8% RH	Unknown	Lab, indoor
Jeffries et al. 2018 (*n* = 10) [69]	33 ± 9	52.4 ± 5.3	Cycling to exhaustion at 70% W_{max} (time to exhaustion)	Per-cooling	(a) Ice slurry ingestion (1.25 g/kg; 0.3 °C) at 85% of baseline time to exhaustion (b) Menthol mouth rinse (25 mL; 19.5 °C) at 85% of baseline time to exhaustion	35 °C/40% RH	Unknown	Lab, indoor
Luomala et al. 2012 (*n* = 7) [70]	32 ± 3	56 ± 3	Cycling in 10-min cycles until exhaustion; 9 min at 60% $VO_{2,max}$, 1 min at 80% $VO_{2,max}$ (time to exhaustion)	Per-cooling	Cooling vest (− 20 °C) from 30 min into exercise until the end	30 °C/40% RH	Unknown	Lab, indoor
Mündel et al. 2006 (*n* = 8) [71]	26 ± 7	54 ± 5	Cycling to exhaustion at 65% W_{max} (time to exhaustion)	Per-cooling	Cold drink ingestion (≥ 300 mL; 3.6° C) during whole trial	33.9 °C/27.9% RH	0.5 m/s (fan)	Lab, indoor
Mündel and Jones 2010 (*n* = 9) [72]	25 ± 7	54 ± 5	Cycling to exhaustion at 65% W_{max} (time to exhaustion)	Per-cooling	Menthol mouth rinse (25 mL every 10 min; 19 °C) during whole trial	34 °C/27% RH	0.5 m/s (fan)	Lab, indoor

Table 2 (continued)

Study	Age (years)	VO_{2max} (mL kg^{-1} min^{-1}) or fitness level	Type of exercise (primary outcome measure)	Type of cooling	Method of cooling	Ambient conditions	Airflow	Lab/field study
Parton et al. 2020 ($n=11$) [73]	20 ± 1	53.9 ± 6.9	Cycling to exhaustion at 16 RPE/'hard or very hard' (time to exhaustion)	Per-cooling	Menthol mouth rinse (25 mL every 10 min; 31.8 °C) during whole trial	34.9 °C/40.6% RH	Unknown	Lab, indoor
Scheadler et al. 2013 ($n=12$) [74]	23 ± 4	53.8 ± 5.2	Running to exhaustion at 75% $VO_{2,max}$ (time to exhaustion)	Per-cooling	Palm cooling device during whole trial	30 °C/50% RH	Unknown	Lab, indoor
Tyler et al. 2011 ($n=8$) [75]	26 ± 2	56.2 ± 9.2	Running to exhaustion at 70% $VO_{2,max}$ (time to exhaustion)	Per-cooling	Neck cooling collar (stored at − 80 °C for 24–28 h, 10 min in ambient conditions) during whole trial	32.2 °C/53% RH	Unknown	Lab, indoor

BM body mass, *lab* laboratory, *min* minutes, *PCM phase change material*, *RH* relative humidity, *RPE* rate of perceived exertion, VO_{2max} maximal oxygen consumption, W_{max} maximal workload

or a fixed RPE (2 out of 16 experiments) protocol. Per-cooling was only used during one time-to-exhaustion protocol. Constant workload exercise performance improvements did not differ for pre-cooling (ES = 0.74, 95% CI 0.50–0.98) (Fig. 5) versus per-cooling (ES = 0.45, 95% CI 0.16–0.74 (Fig. 6), $p = 0.13$). Nevertheless, the magnitude of the ES differed across cooling strategies, with no benefits of limb per-cooling (ES = − 0.18, 95% CI − 0.98 to 0.74) to large benefits of a cooling vest during pre-cooling (ES = 0.81, 95% CI 0.27–1.35) or per-cooling interventions (ES = 1.15, 95% CI 0.30–2.01) (Figs. 5, 6). Statistical heterogeneity was only observed for pre-cooling ($I^2 = 62\%$, $p < 0.001$) studies and not for per-cooling ($I^2 = 36\%$, $p = 0.11$).

3.5 Self-Paced Versus Constant Workload Exercise Studies

The type of exercise protocol impacted the magnitude of performance benefits following cooling interventions, with a smaller improvement following self-paced versus constant workload exercise (ES = 0.30, 95% CI 0.18–0.42 vs ES = 0.62, 95% CI 0.44–0.81, $p = 0.004$). Interestingly, the difference in performance improvement between self-paced and constant workload exercise was only observed with pre-cooling interventions (ES = 0.29, 95% CI 0.17–0.42 vs ES = 0.74, 95% CI 0.50–0.98, $p = 0.001$, Fig. 2 of the ESM), but not with per-cooling interventions (ES = 0.35, 95% CI 0.01–0.70 vs ES = 0.45, 95% CI 0.16–0.74, $p = 0.68$, Fig. 3 of the ESM). Figure 7 provides a graphical summary of the results. Further stratification for exercise duration revealed that differences in the effectiveness of pre-cooling between self-paced and constant workload studies were larger for exercise protocols with a short-to-medium duration (< 40 min) [ES = 0.26, 95% CI 0.09–0.43 vs ES = 0.90, 95% CI 0.62–1.19, $p < 0.001$, Fig. 4 of the ESM). However, this effect was not present for protocols with a medium-to-long duration (> 20 min) [ES = 0.30, 95% CI 0.16–0.43 vs ES = 0.43, 95% CI 0.13–0.73, $p = 0.44$, Fig. 5 of the ESM) or medium duration only (20–40 min) [ES = 0.25, 95% CI 0.05–0.45 vs ES = 0.47, 95% CI 0.04–0.91, $p = 0.36$, Fig. 6 of the ESM).

4 Discussion

The purpose of this meta-analytical review was to compare the magnitude of the performance effect from pre- and per-cooling on self-paced and constant workload exercise performance. For this purpose, data from 40 self-paced and 19 constant workload studies were pooled, representing performance outcomes of 832 paired measurements. We found that pre-cooling provided less performance enhancement during self-paced compared with constant workload exercise

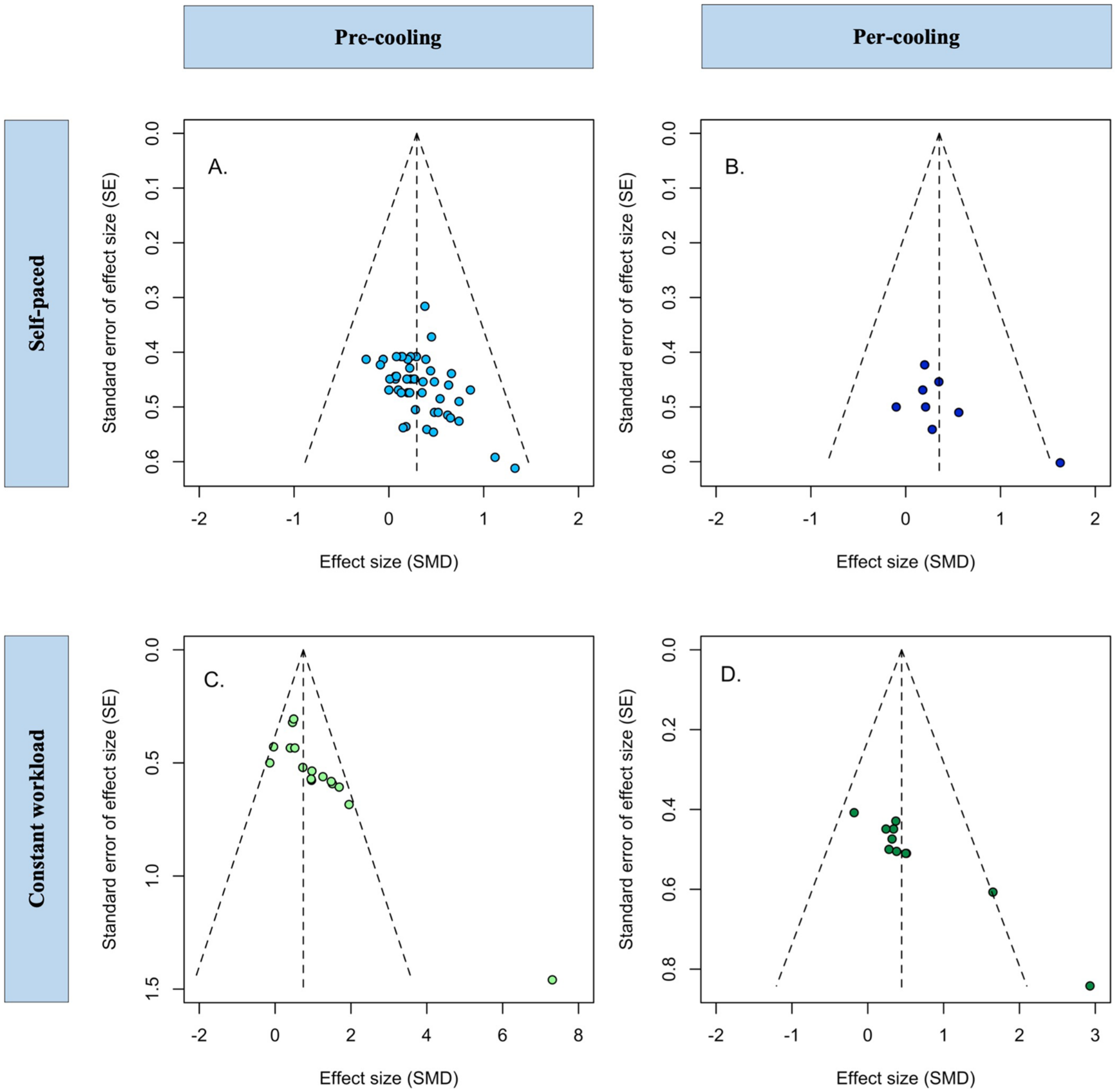


Fig. 2 Funnel plot of included studies separated for self-paced (top figures; **A** and **B**) and constant workload (bottom figures; **C** and **D**) exercise performance; data are also separated for pre-cooling (left figures; **A** and **C**) and per-cooling (right figures; **B** and **D**). A few outliers are observed within figures **B**, **C**, and **D**. The vertical dotted line represents the weighted average effect size of all included studies. *SE* standard error, *SMD* standardized mean difference

in the heat (ES = 0.29, 95% CI 0.17, 0.42 vs ES = 0.74, 95% CI 0.50–0.98), whereas no difference in performance was noted for per-cooling across exercise protocols (ES = 0.35, 95% CI 0.01–0.70 vs ES = 0.45, 95% CI 0.16–0.74). We also observed a large heterogeneity in the benefits of cooling interventions within exercise protocols. These findings have important implications for competitive athletes as the performance benefits of pre-cooling during self-paced exercise may be less than previously assumed.

Cooling interventions did not produce similar performance benefits for self-paced and constant workload exercise in the heat. It was previously suggested that the type of exercise protocol may impact the magnitude of performance benefits [10, 11]. To account for these methodological differences, we calculated Hedges' *g* rather than a percentage improvement, so this could not explain our findings. Alternatively, the duration of the exercise protocol may have contributed to this finding as previous studies suggested that pre-cooling interventions are predominantly effective for an exercise duration of < 40 min [6, 84]. Indeed, longer protocols (i.e., > 40 min) were more common in self-paced compared with constant workload studies (47% vs 34% of included experiments), but exclusion of these studies did not alter the outcomes of our analysis (Fig. 4 of the ESM). We also observed that the constant workload studies with the largest attenuation of decline in exercise

Table 3 Risk of bias, self-paced studies

	Domain 1a: randomization	Domain S: carryover effect	Domain 2: deviations from intended intervention	Domain 3: missing outcome data	Domain 4: measurement of outcome	Domain 5: bias in selection of the reported result
Arngrïmsson 2004	—	+	+	+	+	—
Barwood 2015	—	+	+	+	+	—
Brade 2014	—	+	+	+	+	—
Byrne 2011	—	+	+	+	+	—
Castle 2006	—	+	+	+	+	—
Chaen 2019	—	+	+	+	+	—
Coelho 2021	—	+	+	+	+	—
De Carvalho 2015	—	+	+	+	+	—
Duffield 2003	—	+	+	+	+	—
Duffield 2007	—	+	+	+	+	—
Duffield 2009	—	+	+	+	+	—
Duffield 2010	—	+	+	+	+	—
Duffield 2013	—	+	+	+	+	—
Faulkner 2015	—	+	+	+	+	—
Faulkner 2019	—	+	+	+	+	—
Fiol 2021	—	+	+	+	+	—
Gerrett 2017	—	+	+	+	+	—
Hsu 2005	—	+	+	+	+	—
Ihsan 2010	—	+	+	+	+	—
Katica 2018	—	+	+	+	+	—
Kay 1999	—	+	+	+	+	—
Maia-Lima 2017	—	+	+	+	+	—
Maroni 2018	—	+	+	+	+	—
Maroni 2020	—	+	+	+	+	—
Mazalan 2022	—	+	+	+	+	—
Minett 2011	—	+	+	+	+	—
Minett 2012a	—	+	+	+	+	—
Minett 2012b	—	+	+	+	+	—
Minniti 2011	—	+	+	+	+	—
Moss 2021	—	+	+	+	+	—
Naito 2020	—	+	+	+	+	—
Randall 2015	—	+	+	x	+	—
Skein 2012	—	+	+	+	+	—
Stevens 2016	—	+	+	+	+	—
Stevens 2017b	—	+	+	+	+	—
Sunderland 2015	—	+	+	+	+	—
Thomas 2019	—	+	+	+	+	—
Tyler 2010	—	+	+	+	+	—
Wen 2022	—	+	+	x	+	—
Yanaoka 2022	—	+	+	+	+	—
Zhang 2022	+	+	+	+	+	—

(green) = low risk (yellow) = some concerns (red) = high risk

Table 4 Risk of bias, constant workload studies

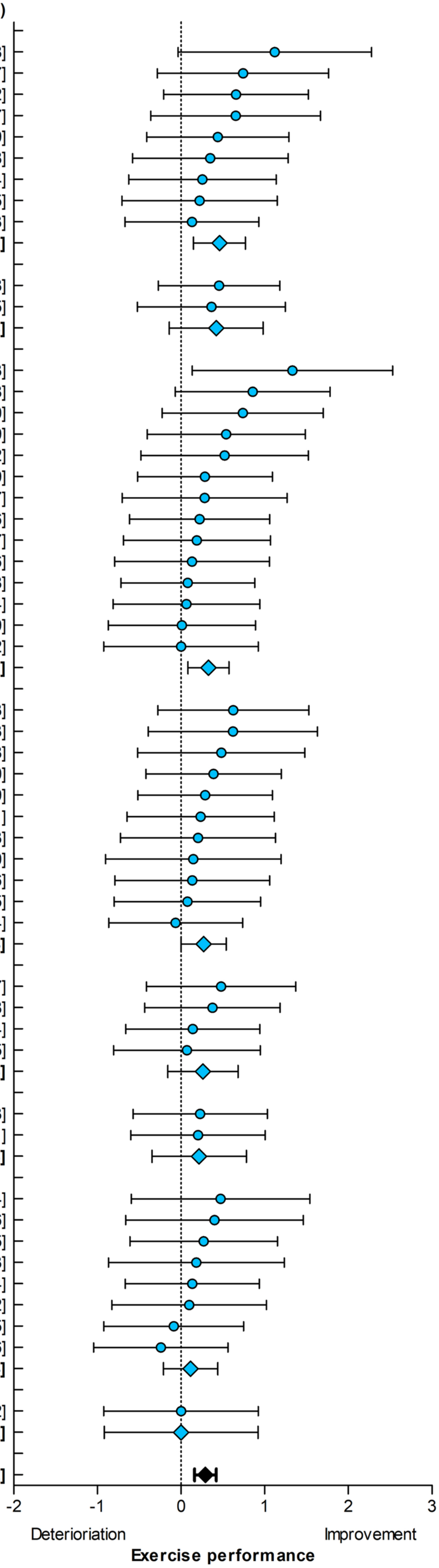
	Domain 1a: randomization	Domain S: carryover effect	Domain 2: deviations from intended intervention	Domain 3: missing outcome data	Domain 4: measurement of outcome	Domain 5: bias in selection of the reported result
Barwood 2019	—	+	+	+	+	—
Choo 2019	—	+	+	+	+	—
Cuttell 2016	—	+	+	+	+	—
Hasegawa 2005	—	+	+	+	+	—
Flood 2017	—	+	+	+	+	—
Jeffries 2018	—	+	+	+	+	—
Luomala 2012	—	+	+	+	+	—
Mitchell 2003	—	+	+	+	+	—
Mündel 2006	—	+	+	+	+	—
Mündel 2010	—	+	+	+	+	—
Nakamura 2020	—	+	+	+	+	—
Osakabe 2021	—	+	+	+	+	—
Parton 2021	+	+	+	+	+	—
Scheadler 2013	—	—	+	+	+	—
Siegel 2012	—	+	+	+	+	—
Tyler 2011	—	+	+	+	+	—
Uckert 2007	—	+	+	+	+	—
Walters 2017	—	+	+	+	+	—
Xu 2021	—	+	+	+	+	—

● = low risk ● = some concerns ● = high risk

performance (i.e., > 50%) used the shortest exercise protocol (i.e., < 20 min) [65, 76, 78]. Stratified analyses without these studies resolved the statistical significance between self-paced and constant workload exercise protocols (Figs. 5 and 6 of the ESM), but the ES of the effectiveness of pre-cooling remained substantially higher for constant workload studies (ES = 0.25, 95% CI 0.05–0.45 vs ES = 0.47, 95% CI 0.04–0.91). These findings indicate that the performance benefits following pre-cooling in self-paced versus constant workload protocols are mediated by exercise duration, with differences mainly present during shorter exercise protocols.

Other explanations for the observed differences may relate to exercise and intervention characteristics. For example, thermal perception is known to impact exercise performance in the heat [85], whereas the magnitude of this effect may be exercise and intervention dependent. Furthermore, the absolute workload, and thus heat production, is likely higher during self-paced exercise compared with constant workload exercise, which could lead to a greater heat storage and associated increments in core temperature, compared with constant workload exercise in comparable environmental conditions. The adopted cooling interventions may not have been powerful enough to compensate for the high rate of metabolic heat production during self-paced protocols. However, mixed-method cooling was more often applied to self-paced versus constant workload experiments (25.0% vs 5.8%, Fig. 1 of the ESM) and we have previously demonstrated that this type of cooling exerts the strongest cooling and performance effects [1, 5]. The cooling strategy that was used does, therefore, not explain our findings. This also applies to airflow, as limited or no airflow could overestimate the benefits of cooling [86], but no differences in airflow characteristics were found between protocols.

Study	Weight (%)	Effect size (95% CI)
Cold w ater immersion		
Kay 1999 [34]	1.3	1.12 [-0.04, 2.28]
Duffield 2010 [64]	1.5	0.74 [-0.28, 1.77]
Zhang 2022 (WCWI) [52]	2.1	0.66 [-0.21, 1.52]
Maia-Lima 2017 [35]	1.6	0.65 [-0.36, 1.67]
Zhang 2022 (LCWI) [52]	2.2	0.44 [-0.41, 1.29]
Yanaoka 2022 [51]	1.8	0.35 [-0.58, 1.28]
Skein 2012 [45]	2.0	0.26 [-0.62, 1.14]
Stevens 2017b [49]	1.8	0.22 [-0.71, 1.15]
Castle 2006 [48]	2.4	0.13 [-0.67, 0.93]
Weighted average ES (95% CI)	**16.7**	**0.46 [0.15, 0.77]**
Head cooling		
Coelho 2021 [60]	3.0	0.45 [-0.27, 1.18]
Minett 2011 [40]	2.1	0.36 [-0.52, 1.25]
Weighted average ES (95% CI)	**5.1**	**0.42 [-0.14, 0.98]**
Mixed methods		
Duffield 2009 [63]	1.2	1.33 [0.13, 2.53]
Minett 2011 [40]	1.8	0.86 [-0.07, 1.78]
Duffield 2007 [62]	1.7	0.74 [-0.23, 1.70]
Duffield 2013 [27]	1.8	0.54 [-0.41, 1.49]
Minett 2012b [42]	1.6	0.52 [-0.48, 1.52]
Brade 2014 [26]	2.4	0.29 [-0.52, 1.09]
Katica 2018 [33]	1.6	0.28 [-0.70, 1.27]
Stevens 2017a [47]	2.2	0.22 [-0.62, 1.06]
Thomas 2019 [50]	2.0	0.19 [-0.69, 1.07]
Moss 2021 (CWI & cold w ater ingestion) [43]	1.8	0.13 [-0.79, 1.06]
Maroni 2018 [36]	2.4	0.08 [-0.72, 0.88]
Maroni 2020 [38]	2.0	0.07 [-0.81, 0.94]
Minett 2012a [41]	2.0	0.01 [-0.87, 0.89]
Moss 2021 (mixed) [43]	1.8	0.00 [-0.92, 0.92]
Weighted average ES (95% CI)	**26.3**	**0.33 [0.08, 0.57]**
Cooling vest		
Faulkner 2015 [28]	2.0	0.63 [-0.28, 1.53]
Faulkner 2019 [29]	1.5	0.62 [-0.39, 1.63]
Chaen 2019 [59]	1.6	0.48 [-0.52, 1.48]
Castle 2006 [48]	2.4	0.39 [-0.42, 1.20]
Brade 2014 [26]	2.4	0.29 [-0.52, 1.09]
Maroni 2020 [38]	2.0	0.23 [-0.65, 1.11]
Arngrimmson 2004 [25]	1.8	0.20 [-0.72, 1.13]
Duffield 2003 [61]	1.4	0.15 [-0.90, 1.20]
Duffield 2007 [60]	1.8	0.13 [-0.79, 1.06]
Thomas 2019 [50]	2.0	0.08 [-0.80, 0.95]
Maroni 2018 [36]	2.4	-0.06 [-0.87, 0.74]
Weighted average ES (95% CI)	**21.3**	**0.27 [0.00, 0.54]**
Limb cooling		
Minett 2011 [40]	2.1	0.48 [-0.41, 1.37]
Castle 2006 [48]	2.4	0.38 [-0.43, 1.18]
Maroni 2018 [36]	2.4	0.14 [-0.66, 0.94]
Maroni 2020 [38]	2.0	0.07 [-0.81, 0.95]
Weighted average ES (95% CI)	**8.9**	**0.26 [-0.16, 0.68]**
Cold air inhalation		
Fiol 2021 (high dose inhalation) [30]	2.4	0.23 [-0.57, 1.03]
Fiol 2021 (low dose inhalation) [30]	2.4	0.20 [-0.60, 1.01]
Weighted average ES (95% CI)	**4.8**	**0.22 [-0.35, 0.78]**
Ice slurry ingestion		
Naito 2020 [44]	1.5	0.47 [-0.60, 1.54]
Ihsan 2010 [32]	1.4	0.40 [-0.66, 1.46]
Thomas 2019 [50]	2.0	0.27 [-0.61, 1.15]
Byrne 2011 [37]	1.4	0.18 [-0.87, 1.23]
Gerrett 2017 [31]	2.4	0.14 [-0.67, 0.94]
Mazalan 2022 [39]	1.8	0.10 [-0.83, 1.02]
Stevens 2016 [46]	2.2	-0.09 [-0.92, 0.75]
Brade 2014 [26]	2.4	-0.24 [-1.05, 0.56]
Weighted average ES (95% CI)	**15.1**	**0.11 [-0.21, 0.44]**
Cooling collar		
Moss 2021 [43]	1.8	0.00 [-0.92, 0.92]
Weighted average ES (95% CI)	**1.8**	**0.00 [-0.92, 0.92]**
Total average ES (95% CI)	**100.0**	**0.29 [0.17, 0.42]**



◂**Fig. 3** Forest plot summarizing the effects of pre-cooling on self-paced exercise performance (effect size [ES] in Hedges' *g*), stratified for cooling interventions and sorted by effect size. The dots represent the ES; the diamonds represent the weighted average ES; the *error bars* indicate the 95% confidence interval (CI). Studies that used multiple cooling trials were included more than once. *CWI* cold water immersion, *LCWI* lower limb cold water immersion, *WCWI* whole-body cold water immersion

The observation that pre-cooling has different benefits on self-paced compared with constant workload exercise performance has important practical implications. The quantification of pre-cooling specific performance benefits that were proposed in previous meta-analyses [8, 87] cannot be translated to self-paced exercise settings, as this overestimated the true effect due to the inclusion of constant-workload studies. Instead, exercise protocol and cooling intervention-specific estimates, as presented in our meta-analysis, provide a more accurate quantification of cooling-induced performance benefits. It is also important to emphasize that the lower effectiveness of pre-cooling in self-paced exercise trials does not disqualify the intervention by itself. After all, a statistically significant performance benefit (ES = 0.29, 95% CI 0.17–0.42) was found for self-paced exercise protocols when using any pre-cooling intervention prior to exercising in the heat compared with a control condition without cooling. Hence, the use of pre-cooling strategies, such as a mixed-method intervention (ES = 0.33), a cooling vest (ES = 0.27), or ice slurry ingestion (ES = 0.11), does provide a performance benefit during self-paced exercise under heat stress. It is also important to highlight that the magnitude of performance benefits was highly context specific, depending on the exercise protocol and the type of cooling, given the large range in ES across different cooling interventions (Fig. 3). Furthermore, in some sports (e.g., marathon running, long-distance cycling), a hybrid pacing strategy is adopted, with a near to constant-workload approach. For optimal laboratory-to-field translation of the ergogenic effects of cooling on performance, the characteristics of the sport and cooling type need both to be considered.

We also found that per-cooling provided comparable performance benefits for self-paced and constant workload exercise protocols. This finding further reinforces the use of per-cooling strategies during competition, as it remains less often applied compared with pre-cooling owing to challenges with practical implementation and the additional weight of a cooling garment [88, 89]. A recent study [90] described practical pre-, per-, and post-cooling methods for racewalking and rugby competition during the Tokyo 2020 Olympics. In both sports, a combination of per-cooling methods was allowed and could be used by athletes during competition. Furthermore, the combination of pre- and per-cooling interventions may be superior to the effectiveness of the cooling interventions in isolation [5], but this could not be addressed in the present analysis because of the limited number of studies that adopted a combination of pre- and per-cooling.

Participants in the included studies had a VO_{2max} of ~ 56 mL kg^{-1} min^{-1}. A previous study [91] showed that the VO_{2max} of elite male athletes ranged between 59 and 77 mL kg^{-1} min^{-1}. As higher aerobic fitness levels have been associated with better thermoregulatory control [92, 93], elite athletes might experience smaller benefits from cooling interventions than we reported, given that they may better cope with heat. In contrast, it has been shown that 98% of elite athletes experience a performance decrement during exercise in hot and humid versus temperate conditions [94]. These observations underline the potential of pre- and per-cooling as valuable heat mitigation strategies for both amateur and elite athletes.

A major strength of this study is the large number of included experiments (n = 86 with 832 paired measurements), as well as the comparison of performance benefits between distinct exercise protocols and the impact of the different pre- and per-cooling interventions on this association. However, some limitations should be considered. First, we excluded 11 studies that combined a constant workload and a self-paced exercise protocol because it was impossible to distinguish the direct effect of cooling on either of the exercise protocols. Second, only data from male individuals were used within this review as very few studies report performance data in female participants. Caution must therefore be used when inferring results from these studies in male individuals directly to female individuals, as female individuals have a limited evaporative capacity at high levels of heat production due to sex-mediated differences in sweat gland output [95]. Given the under-representation of female individuals in exercise science, future studies and a meta-analysis on the benefits of cooling interventions on performance benefits of female athletes during exercise in the heat are warranted. Finally, insufficient data were available to perform stratified analyses for cooling type, cooling dose, exercise type, and training status, thus future meta-analyses should take this into account.

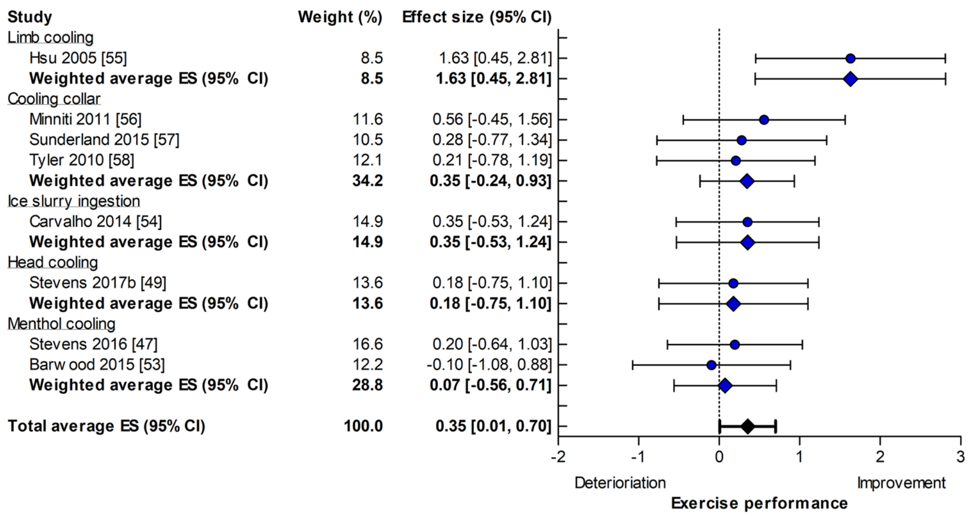


Fig. 4 Forest plot summarizing the effects of per-cooling on self-paced exercise performance (effect size [ES] in Hedges' *g*), stratified for cooling interventions and sorted by ES. The *dots* represent the ES; the diamonds represent the weighted average ES; the error bars indicate the 95% confidence interval (CI). Studies that used multiple cooling trials were included more than once

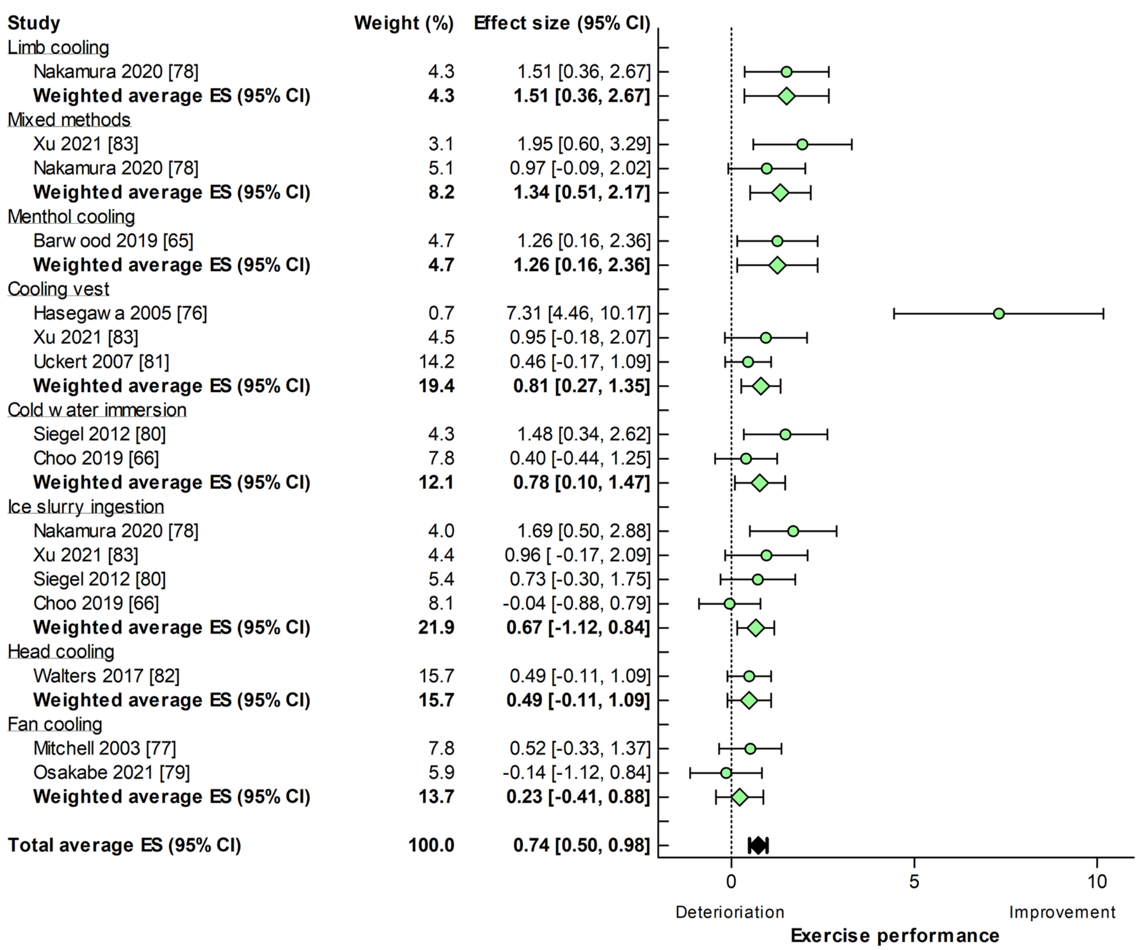


Fig. 5 Forest plot summarizing the effects of pre-cooling on constant workload exercise performance (effect size [ES] in Hedges' *g*), stratified for cooling interventions and sorted by effect size. The dots represent the ES; the diamonds represent the weighted average ES; the error bars indicate the 95% confidence interval (CI). Studies that used multiple cooling trials were included more than once

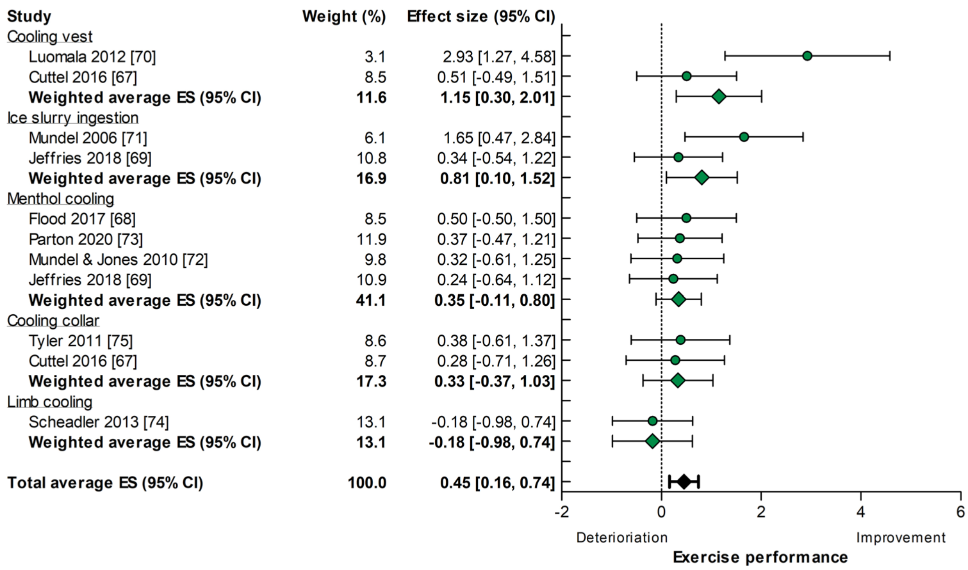


Fig. 6 Forest plot summarizing the effects of per-cooling on constant workload exercise performance (effect size [ES] in Hedges' *g*), stratified for cooling interventions and sorted by effect size. The dots represent the ES; the diamonds represent the weighted average ES; the error bars indicate the 95% confidence interval (CI). Studies that used multiple cooling trials were included more than once

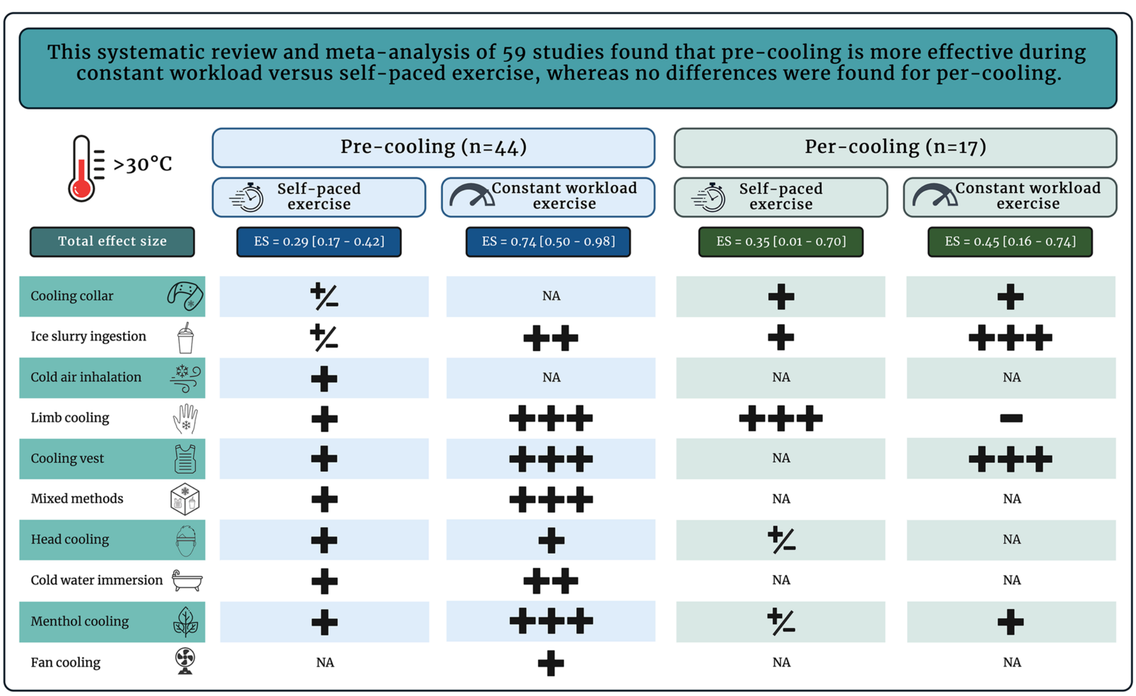


Fig. 7 Graphical summary: effectiveness of pre- and per-cooling strategies on performance outcomes of self-paced versus constant workload exercise protocols. Pre-cooling was more effective for constant workload versus self-paced exercise, whereas no differences were found for per-cooling strategies. The effectiveness of different cooling techniques was also explored. The magnitude of the effect was classified as: < 0.0 = negative (−), 0.0–0.19 = trivial (±), 0.2–0.49 = small (+), 0.5–0.79 = moderate (++), and > 0.8 = large (+++). *ES* effect size, *NA* not available. Created with BioRender.com

5 Conclusions

Cooling interventions attenuate the decline in performance during exercise in the heat, but the magnitude of the effect is dependent on the exercise protocol (self-paced vs constant workload) and type of cooling (pre- vs per-cooling). Pre-cooling appears to be more effective during a constant workload compared with self-paced exercise protocols, whereas no differences were found in the effectiveness of per-cooling. We also observed substantial heterogeneity in the magnitude of performance benefits across different type of cooling interventions, thus additional studies regarding which type of cooling is most effective under specific exercise conditions (e.g., type, duration) are warranted.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s40279-023-01940-y.

Acknowledgements We are grateful to Niels Stens for his assistance with creating the figures.

Declarations

Funding No funding was received to conduct this systematic review and meta-analysis.

Conflicts of Interest/Competing Interests Julien D. Périard and Thijs M.H. Eijsvogels are scientific advisory board members for Inuteq. Tessa M. van de Kerkhof and Coen C.W.G. Bongers have no conflicts of interest that are directly relevant to the content of this article.

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Availability of Data and Material The dataset that was used for the meta-analysis is available upon reasonable request to the corresponding author.

Code Availability Not applicable.

Authors' Contributions TMK, CCWGB, JDP, and TMHE provided the study concept and design. TMK and CCWGB participated in the data acquisition, TMK performed the statistical analysis, and TMK, CCWGB, JDP, and TMHE interpreted the data. TMK drafted the manuscript, whereas CCWGB, JDP, and TMHE critically revised the manuscript for important intellectual content. TMHE supervised this project. All authors read and approved the final version.

References

1. Périard JD, Eijsvogels TMH, Daanen HAM. Exercise under heat stress: thermoregulation, hydration, performance implications, and mitigation strategies. Physiol Rev. 2021;101:1873–9. https://doi.org/10.1152/physrev.00038.2020.
2. Wendt D, van Loon LJC, Marken Lichtenbelt WD. Thermoregulation during exercise in the heat. Sport Med. 2007;37:669–82. https://doi.org/10.2165/00007256-200737080-00002.
3. Casa DJ, DeMartini JK, Bergeron MF, et al. National Athletic Trainers' Association position statement: exertional heat illnesses. J Athl Train. 2015;50:986–1000. https://doi.org/10.4085/1062-6050-50.9.07.
4. Alhadad SB, Tan PMS, Lee JKW. Efficacy of heat mitigation strategies on core temperature and endurance exercise: a meta-analysis. Front Physiol. 2019;10:71. https://doi.org/10.3389/fphys.2019.00071.
5. Bongers CCWG, Hopman MTE, Eijsvogels TMH. Cooling interventions for athletes: an overview of effectiveness, physiological mechanisms, and practical considerations. Temperature (Austin). 2017;4:60–78. https://doi.org/10.1080/23328940.2016.1277003.
6. Wegmann M, Faude O, Poppendieck W, et al. Pre-cooling and sports performance: a meta-analytical review. Sports Med. 2012;42:545–64. https://doi.org/10.2165/11630550-000000000-00000.
7. Bongers CCWG, Thijssen DHJ, Veltmeijer MTW, et al. Precooling and percooling (cooling during exercise) both improve performance in the heat: a meta-analytical review. Br J Sports Med. 2015;49:377–84. https://doi.org/10.1136/bjsports-2013-092928.
8. Tyler CJ, Sunderland C, Cheung SS. The effect of cooling prior to and during exercise on exercise performance and capacity in the heat: a meta-analysis. Br J Sports Med. 2015;49:7–13. https://doi.org/10.1136/bjsports-2012-091739.
9. Roriz M, Brito P, Teixeira FJ, et al. Performance effects of internal pre- and per-cooling across different exercise and environmental conditions: a systematic review. Front Nutr. 2022. https://doi.org/10.3389/fnut.2022.959516.
10. Amann M, Hopkins WG, Marcora SM. Similar sensitivity of time to exhaustion and time-trial time to changes in endurance. Med Sci Sports Exerc. 2008;40:574–8. https://doi.org/10.1249/MSS.0b013e31815e728f.
11. Hopkins WG, Schabort EJ, Hawley JA. Reliability of power in physical performance tests. Sports Med. 2001;31:211–34. https://doi.org/10.2165/00007256-200131030-00005.
12. Bright FM, Clark B, Jay O, et al. The effect of minimal differences in the skin-to-air vapor pressure gradient at various dry-bulb temperatures on self-paced exercise performance. J Appl Physiol. 2021;131:1176–85. https://doi.org/10.1152/japplphysiol.01059.2020.
13. Galloway SD, Maughan RJ. Effects of ambient temperature on the capacity to perform prolonged cycle exercise in man. Med Sci Sports Exerc. 1997;29:1240–9. https://doi.org/10.1097/00005768-199709000-00018.
14. Shamseer L, Moher D, Clarke M, Ghersi D, Liberati A, Petticrew M, Shekelle PSL. PRISMA-P (Preferred Reporting Items for Systematic review and Meta-Analysis Protocols) 2015 checklist: recommended items to address in a systematic review protocol. BMJ. 2015;350: g7647.

15. Wood L, Egger M, Gluud LL, et al. Empirical evidence of bias in treatment effect estimates in controlled trials with different interventions and outcomes: meta-epidemiological study. BMJ. 2008;336:601–5. https://doi.org/10.1136/bmj.39465.451748.AD.
16. Jeffries O, Waldron M. The effects of menthol on exercise performance and thermal sensation: a meta-analysis. J Sci Med Sport. 2019;22:707–15. https://doi.org/10.1016/j.jsams.2018.12.002.
17. WebPlotDigitizer: Version 4.5. 2022. https://automeris.io/WebPlotDigitizer/. (Accessed 24 Sep 2023).
18. Drevon D, Fursa SR, Malcolm AL. Intercoder reliability and validity of WebPlotDigitizer in extracting graphed data. Behav Modif. 2017;41:323–39. https://doi.org/10.1177/0145445516673998.
19. Fritz CO, Morris PE, Richler JJ. Effect size estimates: current use, calculations, and interpretation. J Exp Psychol Gen. 2012;141:2–18. https://doi.org/10.1037/a0024338.
20. Cohen J. Statistical power analysis for the behavioral sciences. Hillsdale (NJ): L. Erlbaum Associates; 1988.
21. Higgins JPT, Thompson SG, Deeks JJ, et al. Measuring inconsistency in meta-analyses. BMJ. 2003;327:557–60. https://doi.org/10.1136/bmj.327.7414.557.
22. Lee CH, Cook S, Lee JS, et al. Comparison of two meta-analysis methods: inverse-variance-weighted average and weighted sum of Z-scores. Genomics Inform. 2016;14:173–80. https://doi.org/10.5808/GI.2016.14.4.173.
23. Randall CA, Ross EZ, Maxwell NS. Effect of practical precooling on neuromuscular function and 5-km time-trial performance in hot, humid conditions among well-trained male runners. J Strength Cond Res. 2015;29:1925–36. https://doi.org/10.1519/JSC.0000000000000840.
24. Wen M, Liu G, Li W, et al. Effects of mixed-cooling strategies on executive functions in simulated tennis in hot and humid conditions. Front Physiol. 2022;13:1008710. https://doi.org/10.3389/fphys.2022.1008710.
25. Arngrïmsson SA, Petitt DS, Stueck MG, et al. Cooling vest worn during active warm-up improves 5-km run performance in the heat. J Appl Physiol. 2004;96:1867–74. https://doi.org/10.1152/japplphysiol.00979.2003.
26. Brade C, Dawson B, Wallman K. Effects of different precooling techniques on repeat sprint ability in team sport athletes. Eur J Sport Sci. 2014;14(Suppl. 1):S84-91. https://doi.org/10.1080/17461391.2011.651491.
27. Duffield R, Coutts A, McCall A, et al. Pre-cooling for football training and competition in hot and humid conditions. Eur J Sport Sci. 2013;13:58–67. https://doi.org/10.1080/17461391.2011.589474.
28. Faulkner SH, Hupperets M, Hodder SG, et al. Conductive and evaporative precooling lowers mean skin temperature and improves time trial performance in the heat. Scand J Med Sci Sports. 2015;25(Suppl. 1):183–9. https://doi.org/10.1111/sms.12373.
29. Faulkner SH, Broekhuijzen I, Raccuglia M, et al. The threshold ambient temperature for the use of precooling to improve cycling time-trial performance. Int J Sports Physiol Perform. 2019;14:323–30. https://doi.org/10.1123/ijspp.2018-0310.
30. Fiol AP, McDermoyy BP, Ridings CB, et al. Effect of breathing cooled air during cycling on physiology and performance in the heat. J Sports Med Phys Fitness. 2021. https://doi.org/10.23736/S0022-4707.21.12770-7.
31. Gerrett N, Jackson S, Yates J, et al. Ice slurry ingestion does not enhance self-paced intermittent exercise in the heat. Scand J Med Sci Sport. 2017;27:1202–12. https://doi.org/10.1111/sms.12744.
32. Ihsan M, Landers G, Brearley M, et al. Beneficial effects of ice ingestion as a precooling strategy on 40-km cycling time-trial performance. Int J Sports Physiol Perform. 2010;5:140–51. https://doi.org/10.1123/ijspp.5.2.140.
33. Katica CP, Wingo JE, Herron RL, et al. Impact of upper body precooling during warm-up on subsequent time trial paced cycling in the heat. J Sci Med Sport. 2018;21:621–5. https://doi.org/10.1016/j.jsams.2017.10.007.
34. Kay D, Taaffe DR, Marino FE. Whole-body pre-cooling and heat storage during self-paced cycling performance in warm humid conditions. J Sports Sci. 1999;17:937–44. https://doi.org/10.1080/026404199365326.
35. Maia-Lima A, Ramos GP, Moraes MM, et al. Effects of precooling on 30-km cycling performance and pacing in hot and temperate environments. Int J Sports Med. 2017;38:48–54. https://doi.org/10.1055/s-0042-113465.
36. Maroni T, Dawson B, Dennis M, et al. Effects of half-time cooling usinga a cooling glove and jacket on manual dexterity and repeated-sprint performance in heat. J Sports Sci Med. 2018;17:485–91.
37. Byrne C, Owen C, Cosnefroy A, et al. Self-paced exercise performance in the heat after pre-exercise cold-fluid ingestion. J Athl Train. 2011;46:592–9. https://doi.org/10.4085/1062-6050-46.6.592.
38. Maroni T, Dawson B, Landers G, et al. Hand and torso pre-cooling does not enhance subsequent high-intensity cycling or cognitive performance in heat. Temperature. 2020;7:165–77. https://doi.org/10.1080/23328940.2019.1631731.
39. Mazalan NS, Landers GJ, Wallman KE, et al. Ice ingestion maintains cognitive performance during a repeated sprint performance in the heat. J Sports Sci Med. 2022;21:164–70. https://doi.org/10.52082/jssm.2022.164.
40. Minett GM, Duffield R, Marino FE, et al. Volume-dependent response of precooling for intermittent-sprint exercise in the heat. Med Sci Sports Exerc. 2011;43:1760–9. https://doi.org/10.1249/MSS.0b013e318211be3e.
41. Minett GM, Duffield R, Kellett A, et al. Mixed-method pre-cooling reduces physiological demand without improving performance of medium-fast bowling in the heat. J Sports Sci. 2012;30:907–15. https://doi.org/10.1080/02640414.2012.679677.
42. Minett GM, Duffield R, Marino FE, et al. Duration-dependant response of mixed-method pre-cooling for intermittent-sprint exercise in the heat. Eur J Appl Physiol. 2012;112:3655–66. https://doi.org/10.1007/s00421-012-2348-2.
43. Moss JN, Trangmar SJ, Mackenzie RWA, et al. The effects of pre- and per-cooling interventions used in isolation and combination on subsequent 15-minute time-trial cycling performance in the heat. J Sci Med Sport. 2021;24:800–5. https://doi.org/10.1016/j.jsams.2021.04.006.
44. Naito T, Haramura M, Muraishi K, et al. Impact of ice slurry ingestion during break-times on repeated-sprint exercise in the heat. Sport Med Int Open. 2020;4:E45-52. https://doi.org/10.1055/a-1139-1761.
45. Skein M, Duffield R, Cannon J, et al. Self-paced intermittent-sprint performance and pacing strategies following respective pre-cooling and heating. Eur J Appl Physiol. 2012;112:253–66. https://doi.org/10.1007/s00421-011-1972-6.
46. Stevens CJ, Thoseby B, Sculley DV, et al. Running performance and thermal sensation in the heat are improved with menthol mouth rinse but not ice slurry ingestion. Scand J Med Sci Sport. 2016;26:1209–16. https://doi.org/10.1111/sms.12555.
47. Stevens CJ, Bennett KJM, Sculley DV, et al. A Comparison of mixed-method cooling interventions on preloaded running performance in the heat. J Strength Cond Res. 2017;31:620–9. https://doi.org/10.1519/JSC.0000000000001532.
48. Castle PC, Macdonald AL, Philp A, et al. Precooling leg muscle improves intermittent sprint exercise performance in hot, humid conditions. J Appl Physiol. 2006;100:1377–84. https://doi.org/10.1152/japplphysiol.00822.2005.

49. Stevens CJ, Kittel A, Sculley DV, et al. Running performance in the heat is improved by similar magnitude with pre-exercise cold-water immersion and mid-exercise facial water spray. J Sports Sci. 2017;35:798–805. https://doi.org/10.1080/02640414.2016.1192294.
50. Thomas G, Cullen T, Davies M, et al. Independent or simultaneous lowering of core and skin temperature has no impact on self-paced intermittent running performance in hot conditions. Eur J Appl Physiol. 2019;119:1841–53. https://doi.org/10.1007/s00421-019-04173-y.
51. Yanaoka T, Iwahashi M, Hasegawa H. Effects of mixed-method cooling between exercise bouts on thermoregulation and cycling time-trial performance in the heat. J Therm Biol. 2022;109: 103329. https://doi.org/10.1016/j.jtherbio.2022.103329.
52. Zhang W, Ren S, Zheng X. Effect of 3min whole-body and lower limb cold water immersion on subsequent performance of agility, sprint, and intermittent endurance exercise. Front Physiol. 2022;13: 981773. https://doi.org/10.3389/fphys.2022.981773.
53. Barwood MJ, Corbett J, Thomas K, et al. Relieving thermal discomfort: effects of sprayed L-menthol on perception, performance, and time trial cycling in the heat. Scand J Med Sci Sport. 2015;25:211–8. https://doi.org/10.1111/sms.12395.
54. De Carvalho MV, De Andrade MT, Ramos GP, et al. The temperature of water ingested ad libitum does not influence performance during a 40-km self-paced cycling trial in the heat. J Sports Med Phys Fitness. 2015;55:1473–9.
55. Hsu AR, Hagobian TA, Jacobs KA, et al. Effects of heat removal through the hand on metabolism and performance during cycling exercise in the heat. Can J Appl Physiol. 2005;30:87–104. https://doi.org/10.1139/h05-107.
56. Minniti A, Tyler CJ, Sunderland C. Effects of a cooling collar on affect, ratings of perceived exertion, and running performance in the heat. Eur J Sport Sci. 2011;11:419–29. https://doi.org/10.1080/17461391.2010.536577.
57. Sunderland C, Stevens R, Everson B, et al. Neck-cooling improves repeated sprint performance in the heat. Front Physiol. 2015;6:314. https://doi.org/10.3389/fphys.2015.00314.
58. Tyler CJ, Wild P, Sunderland C. Practical neck cooling and time-trial running performance in a hot environment. Eur J Appl Physiol. 2010;110:1063–74. https://doi.org/10.1007/s00421-010-1567-7.
59. Chaen Y, Onitsuka S, Hasegawa H. Wearing a cooling vest during half-time improves intermittent exercise in the heat. Front Physiol. 2019;10:711. https://doi.org/10.3389/fphys.2019.00711.
60. Coelho LGM, Ferreira-Júnior JB, Williams TB, et al. Head pre-cooling improves 5-km time-trial performance in male amateur runners in the heat. Scand J Med Sci Sports. 2021;31:1753–63. https://doi.org/10.1111/sms.13985.
61. Duffield R, Dawson B, Bishop D, et al. Effect of wearing an ice cooling jacket on repeat sprint performance in warm/humid conditions. Br J Sports Med. 2003;37:164–9. https://doi.org/10.1136/bjsm.37.2.164.
62. Duffield R, Marino FE. Effects of pre-cooling procedures on intermittent-sprint exercise performance in warm conditions. Eur J Appl Physiol. 2007;100:727–35. https://doi.org/10.1007/s00421-007-0468-x.
63. Duffield R, Steinbacher G, Fairchild TJ. The use of mixed-method, part-body pre-cooling procedures for team-sport athletes training in the heat. J Strength Cond Res. 2009;23:2524–32. https://doi.org/10.1519/JSC.0b013e3181bf7a4f.
64. Duffield R, Green R, Castle P, et al. Precooling can prevent the reduction of self-paced exercise intensity in the heat. Med Sci Sports Exerc. 2010;42:577–84. https://doi.org/10.1249/MSS.0b013e3181b675da.
65. Barwood MJ, Kupusarevic J, Goodall S. Enhancement of exercise capacity in the heat with repeated menthol-spray application. Int J Sports Physiol Perform. 2019;14:644–9. https://doi.org/10.1123/ijspp.2018-0561.
66. Choo HC, Peiffer JJ, Lopes-Silva JP, et al. Effect of ice slushy ingestion and cold water immersion on thermoregulatory behavior. PLoS ONE. 2019;14: e0212966. https://doi.org/10.1371/journal.pone.0212966.
67. Cuttell SA, Kiri V, Tyler C. A Comparison of 2 practical cooling methods on cycling capacity in the heat. J Athl Train. 2016;51:525–32. https://doi.org/10.4085/1062-6050-51.8.07.
68. Flood TR, Waldron M, Jeffries O. Oral L-menthol reduces thermal sensation, increases work-rate and extends time to exhaustion, in the heat at a fixed rating of perceived exertion. Eur J Appl Physiol. 2017;117:1501–12. https://doi.org/10.1007/s00421-017-3645-6.
69. Jeffries O, Goldsmith M, Waldron M. L-Menthol mouth rinse or ice slurry ingestion during the latter stages of exercise in the heat provide a novel stimulus to enhance performance despite elevation in mean body temperature. Eur J Appl Physiol. 2018;118:2435–42. https://doi.org/10.1007/s00421-018-3970-4.
70. Luomala MJ, Oksa J, Salmi JA, et al. Adding a cooling vest during cycling improves performance in warm and humid conditions. J Therm Biol. 2012;37:47–55. https://doi.org/10.1016/j.jtherbio.2011.10.009.
71. Mündel T, King J, Collacott E, et al. Drink temperature influences fluid intake and endurance capacity in men during exercise in a hot, dry environment. Exp Physiol. 2006;91:925–33. https://doi.org/10.1113/expphysiol.2006.034223.
72. Mundel T, Jones DA. The effects of swilling an L(-)-menthol solution during exercise in the heat. Eur J Appl Physiol. 2010;109:59–65. https://doi.org/10.1007/s00421-009-1180-9.
73. Parton AJ, Waldron M, Clifford T, et al. Thermo-behavioural responses to orally applied l-menthol exhibit sex-specific differences during exercise in a hot environment. Physiol Behav. 2021;229: 113250. https://doi.org/10.1016/j.physbeh.2020.113250.
74. Scheadler CM, Saunders NW, Hanson NJ, et al. Palm cooling does not improve running performance. Int J Sports Med. 2013;34:732–5. https://doi.org/10.1055/s-0032-1327576.
75. Tyler CJ, Sunderland C. Cooling the neck region during exercise in the heat. J Athl Train. 2011;46:61–8. https://doi.org/10.4085/1062-6050-46.1.61.
76. Hasegawa H, Takatori T, Komura T, et al. Wearing a cooling jacket during exercise reduces thermal strain and improves endurance exercise performance in a warm environment. J strength Cond Res. 2005;19:122–8. https://doi.org/10.1519/14503.1.
77. Mitchell JB, McFarlin BK, Dugas JP. The effect of pre-exercise cooling on high intensity running performance in the heat. Int J Sports Med. 2003;24:118–24. https://doi.org/10.1055/s-2003-38203.
78. Nakamura D, Muraishi K, Hasegawa H, et al. Effect of a cooling strategy combining forearm water immersion and a low dose of ice slurry ingestion on physiological response and subsequent exercise performance in the heat. J Therm Biol. 2020;89: 102530. https://doi.org/10.1016/j.jtherbio.2020.102530.
79. Osakabe J, Kajiki M, Kondo K, et al. Effects of half-time cooling using a fan with skin wetting on thermal response during intermittent cycling exercise in the heat. Sport Med Int Open. 2021;5:E91–8. (**10.1055a-1588-3126**).
80. Siegel R, Maté J, Watson G, et al. Pre-cooling with ice slurry ingestion leads to similar run times to exhaustion in the heat as cold water immersion. J Sports Sci. 2012;30:155–65. https://doi.org/10.1080/02640414.2011.625968.
81. Ückert S, Joch W. Effects of warm-up and precooling on endurance performance in the heat. Br J Sports Med. 2007;41:380–4. https://doi.org/10.1136/bjsm.2006.032292.

82. Walters P, Thom N, Libby K, et al. The effect of intermittent head cooling on aerobic performance in the heat. J Sport Sci Med. 2017;16:77–83.
83. Xu M, Wu Z, Dong Y, et al. A mixed-method approach of pre-cooling enhances high-intensity running performance in the heat. J Sports Sci Med. 2021;20:26–34. https://doi.org/10.52082/jssm.2021.26.
84. Drust B, Cable NT, Reilly T. Investigation of the effects of the pre-cooling on the physiological responses to soccer-specific intermittent exercise. Eur J Appl Physiol Occup Physiol. 2000;81:11–7. https://doi.org/10.1007/PL00013782.
85. Kroesen SH, de Korte JQ, Hopman MTE, et al. Impact of thermal sensation on exercise performance in the heat: a thermo Tokyo sub-study. Eur J Appl Physiol. 2021. https://doi.org/10.1007/s00421-021-048458.
86. Morrison SA, Cheung S, Cotter JD. Importance of airflow for physiologic and ergogenic effects of precooling. J Athl Train. 2014;49:632–9. https://doi.org/10.4085/1062-6050-49.3.27.
87. Jones PR, Barton C, Morrissey D, et al. Pre-cooling for endurance exercise performance in the heat: a systematic review. BMC Med. 2012. https://doi.org/10.1186/1741-7015-10-166.
88. Périard JD, Racinais S, Timpka T, et al. Strategies and factors associated with preparing for competing in the heat: a cohort study at the 2015 IAAF World Athletics Championships. Br J Sports Med. 2017;51:264–70. https://doi.org/10.1136/bjsports-2016-096579.
89. Alkemade P, Daanen HAM, Janssen TWJ, et al. Heat preparedness and exertional heat illness in paralympic athletes: a Tokyo 2020 survey. Temperature. 2022. https://doi.org/10.1080/23328940.2022.2147364.
90. Taylor L, Carter S, Stellingwerff T. Cooling at Tokyo 2020: the why and how for endurance and team sport athletes. Br J Sports Med. 2020;54:1243–5. https://doi.org/10.1136/bjsports-2020-102638.
91. Nevill AM, Brown D, Godfrey R, et al. Modeling maximum oxygen uptake of elite endurance athletes. Med Sci Sports Exerc. 2003;35:488–94. https://doi.org/10.1249/01.MSS.0000053728.12929.5D.
92. Boegli Y, Gremion G, Golay S, et al. Endurance training enhances vasodilation induced by nitric oxide in human skin. J Invest Dermatol. 2003;121:1197–204. https://doi.org/10.1046/j.1523-1747.2003.12518.x.
93. Kvernmo HD, Stefanovska A, Kirkebøen KA, et al. Enhanced endothelium-dependent vasodilatation in human skin vasculature induced by physical conditioning. Eur J Appl Physiol Occup Physiol. 1998;79:30–6. https://doi.org/10.1007/s004210050469.
94. de Korte JQ, Bongers CCWG, Hopman MTE, et al. Exercise performance and thermoregulatory responses of elite athletes exercising in the heat: outcomes of the thermo Tokyo study. Sport Med. 2021;51:2423–36. https://doi.org/10.1007/s40279-021-01530-w.
95. Gagnon D, Kenny GP. Sex differences in thermoeffector responses during exercise at fixed requirements for heat loss. J Appl Physiol. 2012;113:746–57. https://doi.org/10.1152/japplphysiol.00637.2012.