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The Effect of Pre-Exercise Cooling on Performance Characteristics: A Systematic Review and Meta-Analysis

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Abstract

Exercising in high environmental temperatures may cause precocious hyperthermia induced fatigue resulting in a decreased athletes' performance output. This systematic review with meta-analysis investigated the possible effects of pre-exercise cooling on performance output. This study was performed according to the PRISMA guidelines and the PICO-model was used to establish the research question. The Cochrane Risk of Bias Tool was applied to assess the validity of the included studies. Study eligibility was given when the studies compared the effects between any kind of pre-cooling and non-cooling strategies prior to exercise on performance output. Twenty-nine studies met the inclusion criteria for quantitative analysis. Risk of bias was high or unclear but the performance bias was low. The estimated standardized mean difference revealed that external pre-cooling (21 studies) enhanced performance (Hedges' g = 0.49 [95% CI: 0.33 to 0.64]), with the main effect observed in endurance cycling or running. Internal (7 studies) and mixed-method (5 studies) pre-cooling failed to significantly affect performance parameters. However, the main output parameter, evaluated in these studies, was peak power output. Subgroup analysis for different outcome measures was not possible because meaningful grouping was not plausible. Limitations of this meta-analysis were the high or unclear risk of bias and the comparability of the included studies. Future studies should also determine the effects of different pre-cooling applications on female and untrained participants. Based on the results of this meta-analysis, it can be concluded that there is some evidence in favour of external pre-cooling to avoid precocious hyperthermia induced fatigue in endurance athletes exercising in hot environments.

Keywords

Performance Cooling, Precooling, Core Temperature, Exercise, Meta-Analysis

1. Introduction

High environmental temperatures may negatively influence the athletes' performance output due to precocious hyperthermia induced fatigue [1] [2]. Various studies have demonstrated that a hot environment is an important factor which may significantly reduce athletes' power output, especially in endurance sport types such as running sports [3] and cycling [4] [5]. At environmental conditions above 30˚C, core temperature over 40˚C and coinciding increased brain temperature, performance will be impaired [6] [7] [8] [9]. Under these circumstances, the athlete's thermoregulatory system will try to decrease core temperature to maintain physical performance. The most effective way of heat dissipation from the body is the evaporation of sweat, also in case of systemic diseases [10]. Therefore, the thermoregulation depends strongly on sweat production and sweat evaporation from the skin [11] [12]. Nybo *et al.* (2014) comprehensively reviewed the existing literature of the last century on the physiological mechanisms that lead to hyperthermia induced fatigue. The authors concluded that various interdepending factors, such as psychological factors, respiration, peripheral and central fatigue factors, neurobiological changes and cardiovascular changes may lead to precocious fatigue during prolonged exercise in the heat [1]. To combat the debilitating effects of hyperthermia induced fatigue, athletes were encouraged to acclimatize to hot environmental conditions [13]. Another strategy to prevent hyperthermia induced fatigue is pre-cooling the body before exercising in the heat. The latter has been demonstrated to increase the heat storage capacity before a critical, performance limiting temperature is reached [14] [15]. As the temperature gradient between the body core and the skin narrows during exercise, blood flow of the skin must be increased to maintain the heat transfer [16] [17]. Additionally, heart rate must be increased for an adequate cardiac output [18]. Consequently, an artificially increased margin between the core temperature and the environmental temperature might be an important factor that leads to an advantage from pre-cooling on performance [19]. Another performance limiting factor seems to be the impaired cardiovascular function to maintain adequate oxygen delivery to the working muscles [18] [20]. Beside reduced metabolism, the increase of intramuscular temperature might lead to impaired mitochondrial functioning, disturbances of K^+, Ca^{2+} and phosphate homeostasis which leads to decreased muscle contractility [21] [22] [23]. Pre-cooling to maintain or enhance sports performance, is a practical on-field strategy for athletes because of its easy implementation during the warm-up period. Various forms of pre-cooling are already practiced and scientifically investigated. External pre-cooling strategies aim to reduce core temperature by decreasing skin and muscle temperature, including the use of ice-vests [24], cold-packs [25], cold-water immersion (CWI) [26] and combinations of cooling different body parts [27]. Internal pre-cooling aims to reduce core temperature and can be performed by ingesting cold water [28] or crushed ice [29] while mixed-method pre-cooling usually contains the combination of ingesting cold water or ice plus an additional partial body cooling application [30]. In a systematic review, Ross *et al.* (2013) evaluated the effectiveness of pre-cooling during field-based sports performance [31]. The findings of this study are in line with another meta-analytical review from Wegmann *et al.* (2012) who indicated that the effects of pre-cooling on performance output are larger in hot (>26˚C) environmental conditions than under moderate (18˚C - 26˚C) temperatures [32]. Although the bulk of literature is growing in this field, a consensus about which cooling method is the most effective [28] and which performance parameter is the most affected under hot temperature conditions is still lacking [2]. Therefore, the aim of this study was to systematically search and critically evaluate the current literature on the effects of external cooling, internal cooling and mixed-method cooling prior to exercise in comparison to non-cooling strategies on different performance parameters of humans exercising under "hot" as well as under "hot and humid" environmental conditions.

2. Methods

2.1. Research Question

The research question was defined by the PICO-model in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [33]: Population: healthy, non-injured athletes and active participants; Intervention: external cooling or internal cooling or mixed-method cooling (combination of external and internal cooling) prior to a specified exercise protocol; Comparator: passive non-cooling strategies; Outcomes: time to finish, time to exhaustion, speed, covered distances and peak power output (PPO).

2.2. Literature Search Strategies and Data Sources

An electronic systematic search, according to the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement, was conducted between October 2016 and January 2017 on the MEDLINE (PubMed) database [34]. Studies were included when meeting the following criteria: 1) internal cooling or external cooling or mixed-method cooling was conducted prior to a specified exercise protocol, 2) the cooling strategies had to be compared with a passive strategy that did not use any kind of cooling procedure, 3) hot environmental conditions (>26˚C), 4) participants were healthy humans without any physical infirmity, 5) male and female study participants were included, 6) written in English or German, 7) written full-text studies had to be published within the last 10 years (2006-2016), 8) the studies had to be randomized controlled trials (RCT) or randomized cross-over trials (RCO). The keywords which best fitted the research question were: “Pre-cooling”, “Precooling”, “Cold”, “Performance” and “Exercise”. These keywords were inserted as follows: (“Pre-cooling” OR “Precooling” OR “Cold”) AND “Performance” AND “Exercise”. The keywords “Pre-cooling”, “Precooling” and “Cold” were used individually, in any order and always combined with (“Performance” AND “Exercise”). After screening and processing all the articles found (k = 668), a total of 29 articles were eligible as sources of primary literature for this meta-analysis. Figure 1

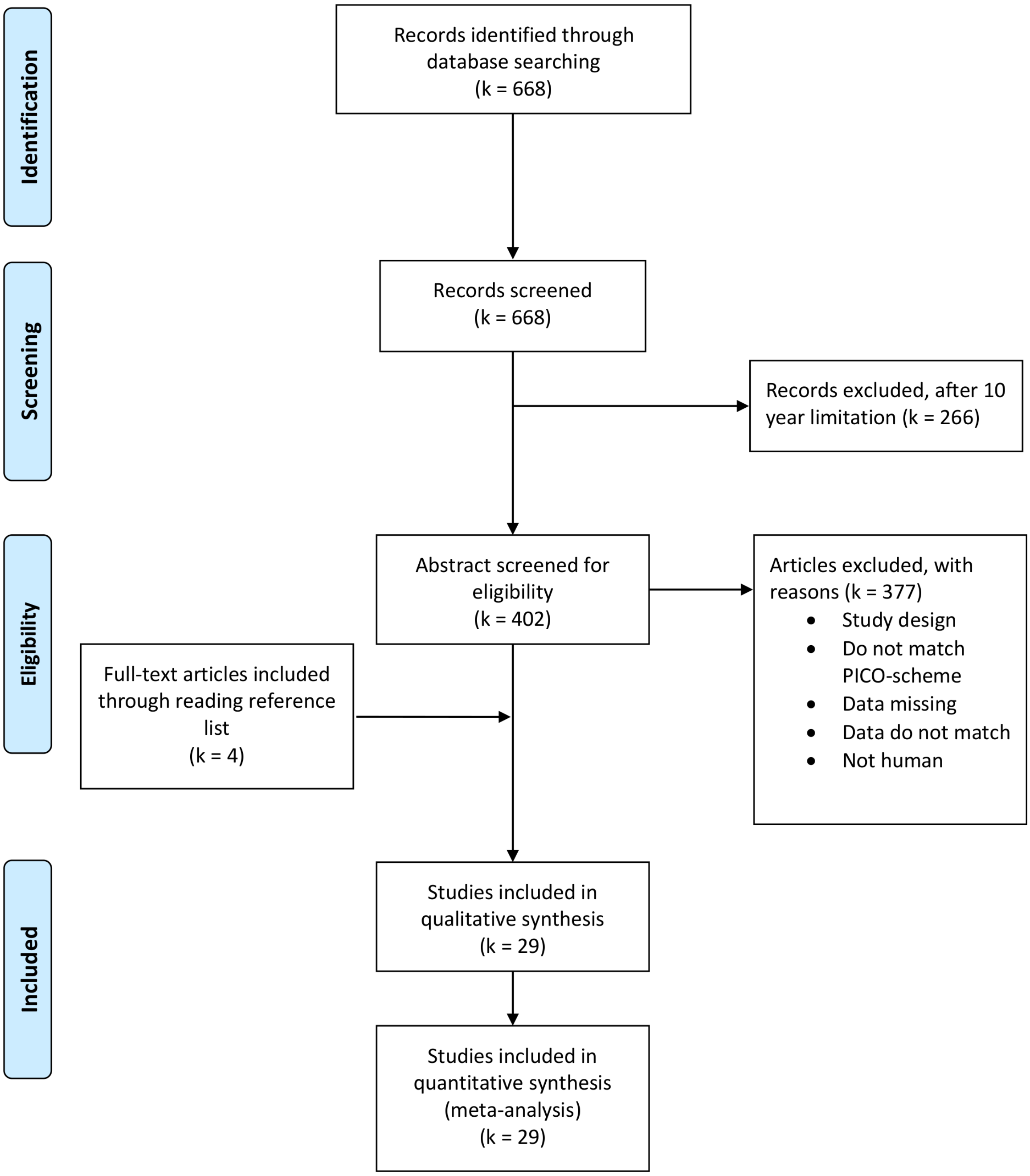

Figure 1. Flow-chart describing the selection process.

shows the flow-chart of the selection process.

2.3. Data Extraction and Quality Assessment

Data extraction from the studies was performed by two researchers (EH, RC). These authors extracted independently from each other the data into spreadsheets. This method was used to extract relevant data on study eligibility and content of the study (including the cooling procedure, environmental conditions, exercise protocols and outcome measures). In case of disagreement, a third researcher (RS) checked the variable in the original study and agreement was sought by consensus. The primary outcomes considered in this meta-analysis were time to finish or exhaustion, maximum speed, covered distance or PPO of a specified exercise task. Data were extracted at the end of the performance of a specified exercise. The methodological quality of the studies was assessed with the Cochrane Risk of Bias Tool [35]. Two researchers independently evaluated the 29 studies (RS, RC). A third researcher (EH) rated in case of disagreement and agreement was sought by consensus.

2.4. Data Analysis

Several meta-analyses and forest plot drawings were conducted using the Comprehensive Meta-Analysis software (CMA II, Biostat Inc., Englewood, NJ 07631, US). A priori it was decided to use a random-effects model because the studies under investigation were not exact replicates of each other. The DerSimonian and Laird inversed-variance method was used to calculate the weighting factors. Because individual studies reported study results in different metrics, the calculated individual study effect sizes were standardized and expressed as Hedges' g to correct for overestimation of the true effect size in small study samples. The corresponding 95% confidence intervals (95% CI) around the individual studies effect sizes as well as around the overall weighted effect were calculated. The latter indicates the range in which the mean effect size may fall, based on the universe from which this set of studies was sampled. Cohen's benchmarking for the interpretation of the effect size was followed: g lower than 0.2 (neglible effect size), g between 0.21 and 0.49 (small effect size), g between 0.50 and 0.79 (moderate effect size), and g equal to or higher than 0.8 (very high effect size) [36].

To test the Null hypothesis of heterogeneity (*i.e.* that all studies have a common effect size), a Cochran's Q-test was conducted and the Q-value was reported together with its corresponding degrees of freedom (df(Q)) and exact *p*-value. The significance level of this Q-test was set at 0.1 because this test is known to lack statistical power. Higgins' I^2 was calculated to express the amount of the total observed variance that can be explained by the true between studies variance rather than random sampling error and was reported as a relative number (*i.e.* in %). Higgins' suggested benchmarking values for the interpretation of I^2 was followed: I^2 around 25% (low heterogeneity), I^2 around 50% (moderate heterogeneity) and I^2 around 75% or more (high heterogeneity) [37]. To give the reader a more absolute estimate of the distribution of possible true effect sizes on population level T^2 (*i.e.* the variance of the distribution of true effects) and its square root (*i.e.* the standard deviation of the distribution of true effect sizes) were calculated. The latter allowed for the calculation of the 95% prediction intervals (95% PI), indicating the range in which the effect-size will fall in most populations. The latter was marked as a horizontal line through the diamond representing the overall weighted mean estimate on the forest-plots.

Subgroup meta-analysis was conducted to explain a part of the observed heterogeneity only if this was plausible (*i.e.* in case of a sufficient number of studies). Groups were established based on the type of exercise protocols (cycling, running and functional strength) and outcomes (cycle time to exhaustion, cycle time to finish, power output, running distance, running time, running time to exhaustion, sprint time and lifted weight) used in the individual studies. Because of the low numbers of studies within the subgroups it was decided to assume a common variance. Thus, to obtain a more accurate value of T^2 in the subgroup analysis, T^2 was pooled and used as the common between studies variance across all the subgroups.

The likelihood for publication bias was assessed only in the overall meta-analysis using the classic fail-safe N and the Duval and Tweedie's trim and fill methods [38].

3. Results

3.1. Risk of Bias Analysis

Figure 2 depicts the Risk of Bias results of each included study and **Figure 3** demonstrates the overview of all included studies for this analysis. Blinding of the participants was not possible in these studies. However, it was not always clear if other members of the research teams were blinded. Similarly, for nearly all other items (with the exception of reporting bias) the raters were uncertain. Thus, methodological issues in the studies under investigation may not be excluded. A low risk of reporting bias was observed in 90% of the analysed studies. For the remaining three studies (10%), reporting bias remained unclear [39] [40] [41]. Additionally, it can be observed that the risk for selection bias (93% for sequence generation and 97% for allocation concealment) detection bias (100% for blinding of outcome assessment) and other bias (100%) remained unclear.

3.2. Study Characteristics

In the present work, the results of eight studies with healthy and active volunteers (k = 91), four studies with team-sport players (k = 49), eight studies with moderately trained (k = 57) and nine studies with well trained volunteers (k = 81) were included in different meta-analyses. Hence, a total of 278 participants (k = 272 males and k = 6 females [42] [43]) were included. The mean environmental temperature in the included studies was 32.3˚C ± 2.2˚C and mean relative humidity 53.9% ± 13.5%. The used exercise testing-protocols varied between

Author	Random sequence generation (selection bias)	Allocation concealment (selection bias)	Blinding of participants and personell (performance bias)	Blinding of outcome assessment (detection bias)	Incomplete outcome data (attrition bias)	Selective reporting (reporting bias)	Other bias
Bogerd 2010	-	?	-	?	?	+	?
Brade 2013a	?	?	-	?	?	+	?
Brade 2013b	?	?	-	?	+	+	?
Brade 2014	?	?	-	?	?	?	?
Byrne 2011	?	?	-	?	?	+	?
Castle 2006	?	?	-	?	?	+	?
Duffield 2007	?	?	-	?	?	+	?
Duffield 2009	?	?	-	?	?	+	?
Duffield 2010	?	?	-	?	?	+	?
Duffield 2011	?	?	-	?	?	+	?
Faulkner 2015	?	?	-	?	?	+	?
Galoza 2011	?	?	-	?	?	?	?
Gonzales 2014	?	?	-	?	?	?	?
Hue 2013	?	?	-	?	?	+	?
Ihsan 2010	?	?	-	?	+	+	?
James 2015	?	?	-	?	?	+	?
Lee 2008	+	-	-	?	?	+	?
Minett 2011	?	?	-	?	?	+	?
Minett 2012a	?	?	-	?	?	+	?
Minett 2012b	?	?	-	?	?	+	?
Morrison 2014	?	?	-	?	?	+	?
Quod 2008	?	?	-	?	?	+	?
Randall 2015	?	?	-	?	?	+	?
Ross 2010	?	?	-	?	-	+	?
Ross 2012	?	?	-	?	-	+	?
Siegel 2012	?	?	-	?	?	+	?
Skein 2012	?	?	-	?	?	+	?
Tyler 2011	?	?	-	?	?	+	?
Ueckert 2007	?	?	-	?	?	+	?

Figure 2. Risk of bias graph for each included study.

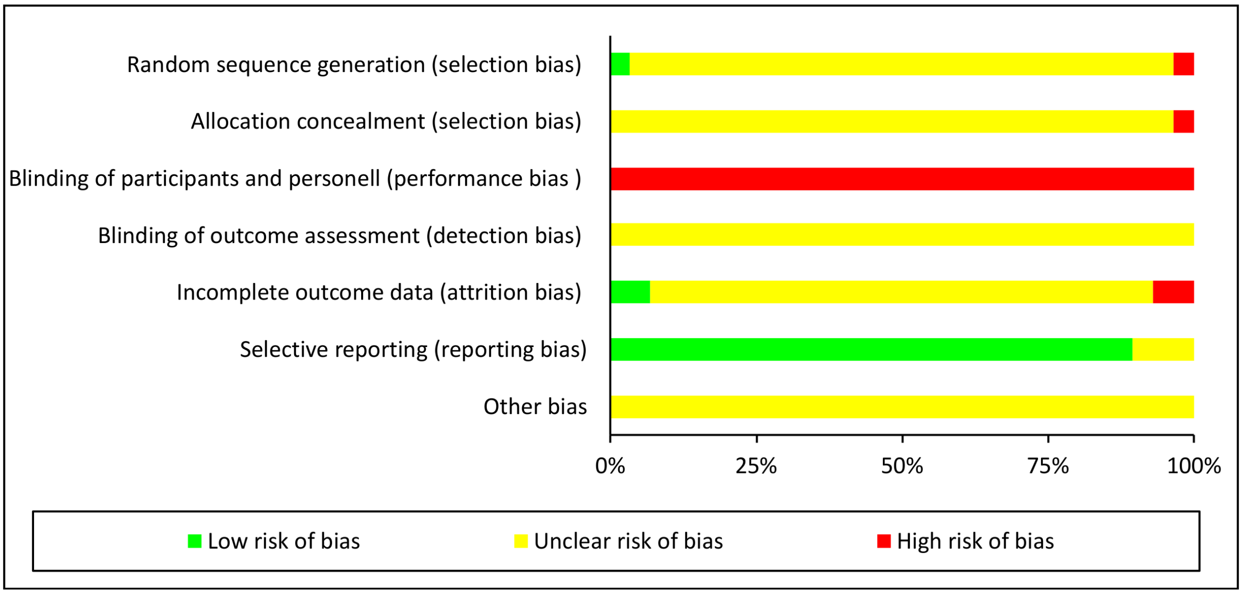

Figure 3. Risk of bias summary for all included studies.

endurance cycling (k = 11) or running (k = 5), repeated cycling (k = 3) or running (k = 6) sprints and sport specific tasks (k = 4). Table 1 depicts a summary of the included studies.

External cooling techniques comprised of cooling vests (k = 4), local ice applications (k = 4), cold-water immersion (CWI; k = 3), combinations of external cooling (k = 11) and whole-body cryotherapy (WBC; k = 1). In total, 23 external cooling data sets were extracted from 21 studies.

Internal cooling techniques comprised of ingesting cold water (k = 3) and crushed ice/ice slurry/slushies (k = 4). In total, seven internal cooling data sets were extracted from seven studies. Mixed-method cooling comprised of the combination of ingesting ice slushies and waring cooling vests (k = 3) or ice towel applications (k = 2). In total, five mixed-method cooling data sets were extracted from five studies comprising of ingesting ice/drinking slushies and wearing cooling vests [39] [44] [45] or using ice towels [30] [46].

3.3. External-Cooling vs. Non-Cooling Strategies

In these analysis, the effects of external cooling was studied on following outcome variables: PPO (k = 5) [25] [39] [40] [41] [47], time to exhaustion (k = 8) [5] [15] [24] [48] [49] [50] [51] [52], covered distance (k = 5) [26] [27] [42] [53] [54] and speed (k = 3) [55] [56] [57]. Six studies investigated the effects of pre-cooling on endurance cycling [5] [24] [41] [47] [48] [49], five studies on endurance running [15] [50] [51] [52] [55], two on repeated cycle sprints [25] [39], five studies on repeated running sprints [26] [27] [53] [54] [57] and three studies on sport specific performance [40] [42] [56]. Authors used ice vests [24] [39] [50] [52], local cooling applications [25] [40] [50] [51], CWI [15] [26] [48] and combinations of external cooling methods [5] [27] [41] [42] [47] [49] [53] [54] [55] [56] [57].

Table 1. Summary of the included studies for the meta-analyses.

Authors	Sample size	Cooling method	Cooling duration	Environmental conditions: Temp (˚C)	Environmental conditions: RH (%)	Exercise protocol	Outcome	*p*-value for cooling vs. control
Bogerd *et al.* (2010)	k = 8 males	Ice vest	45 min	29	80	Endurance cycling at 65% VO_{2max}	Cycle time to exhaustion	<0.001
Brade *et al.* (2013)[a]	k = 10 males	Slushy & cooling vest	Ingesting 7 g/kg ice every 10 min up to 30 min & 8 min (vest)	27	N/a	Repeated sprint running for 80 min	Sprint time	0.64
Brade *et al.* (2013)[b]	k = 10 males	Slushy & cooling vest	Ingesting 7g/kg ice every 10 min up to 30 min & 8 min (vest)	35	58	Repeated cycling sprint for 70 min	PPO	0.60
Brade *et al.* (2014)	k = 12 males	Ice Vest & Slushy. + Ice Vest. + Slushy	Vest worn and ingesting 7 g/kg ice for max. 30 min. + vest worn for max. 30 min. + ingesting 7 g/kg ice up to 30 min.	35	60	Repeated cycling sprint for 70 min	PPO	0.22+ 0.28+ 0.28
Byrne *et al.* (2011)	k = 7 males	Ingesting cold water	Ingesting 900 ml of cold water (2˚C) during 35 min	32	60	30 min self-paced cycling trial	PPO	0.04
Castle *et al.* (2006)	k = 12 males	Ice packs on upper legs	20 min	34	52	Intermittent cycling sprint for 20 × 5 sec	PPO	0.01
Duffield *et al.* (2007)	k = 9 males	CWI	15 & 10 min	32	30	Intermittent sprint protocol for 2 × 30 min	Running distance	0.33
Duffield *et al.* (2009)	k = 7 males	Cooling vest & cold towels to the neck & ice packs on the upper legs	20 min	32	44	Intermittent sprint exercise for 30 min	Running distance	0.001
Duffield *et al.* (2010)	k = 8 males	CWI	20 min	33	50	Cycle time trial for 40 min	PPO	0.01
Duffield *et al.* (2011)	k = 6 males and k = 2 females	Ice vest & cold towels to the neck & head	20 min	35	55	On court tennis drills for 5 × 5 min	Running distance	0.13
Faulkner *et al.* (2015)	k = 10 males	Cooling vest & cooling sleeves	9 min	35	50	Cycling 60 min at 75% W_{max} as fast as possible	PPO	0.03
Galoza *et al.* (2011)	k = 16 males	Ice bags on the upper arm	3 × 1 min	n/a	n/a	4 sets of biceps curls at 70% of 1 RM	Weight lifted	0.05
Gonzales *et al.* (2014)	k = 10 males	Cooling vest & headband	5 & 15 min	30	79	Cycle time trial for 20 min	PPO	0.01
Hue *et al.* (2013)	k = 5 males and k = 4 females	Ingesting ice water	Ingesting 190 ml water before exercise	28	73	10 × 100 m swimming	Swimming time	0.66
Ihsan *et al.* (2010)	k = 7 males	Ingesting crushed ice	Ingesting 6.8 g/kg ice within 30 min	30	75	Cycle time trial for 40 min	PPO	0.12
James *et al.* (2015)	k = 12 males	Ice slurry + Cold towels to the neck and head & water immersion of hands & cooling vest & ice packs on upper legs	Ingesting 7.5 g/kg of ice within 20 min + 20 min	32	62	Incremental treadmill test	Running speed	0.73 (HI), 0.63 (LI)+ 0.27 (HI), 0.14 (LI)
Lee *et al.* (2008)	k = 8 males	Ingesting cold drink	3 bottles of 300 ml of old water within 20 min each bottle in 2 min.	35	69	Cycling at 65% VO_{2max} until exhaustion	Cycle time to exhaustion	<0.001
Minett *et al.* (2011)	k = 10 males	Cold towels to the neck and head & water immersion of hands & cooling vest & ice packs on upper legs	20 min	33	33	Intermittent sprint protocol for 2 × 35 min	Running distance	0.003

Continued

Minett *et al.* (2012)[a]	k = 8 males	Cold towels to the neck and head & water immersion of hands & cooling vest & ice packs on upper legs	20 min	33	34	Intermittent sprint protocol for 2 × 35 min	Running distance	0.001
Minett *et al.* (2012)[b]	k = 10 males	Cold towels to the neck and head & water immersion of hands & cooling vest & ice packs on upper legs	20 min	32	64	6-over spell bowling performance	Running speed	0.83
Morrison *et al.* (2014)	k = 10 males	CWI	60 min	30	50	Cycling at 95% of ventilatory threshold until exhaustion	Cycle time to exhaustion	0.001
Quod *et al.* (2008)	k = 6 males	CWI & cooling vest	30 min (CWI) & 40 min (cooling vest)	34	41	Cycle time trial for 40 min	Cycle time to finish	0.008
Randall *et al.* (2015)	k = 8 males	Cooling vest + ice packs on upper legs	30 min + 30 min	32	48	Treadmill running at 70% VO_{2max} until exhaustion	Running time	0.22 + 0.002
Ross *et al.* (2011)	k = 11 males	Cold towels & ingesting ice	Ingesting 14 g/kg of ice while wearing cold towels 30 min	34	55	Cycle time trial of 46.4 km	PPO	0.04
Ross *et al.* (2012)	k = 12 males	Cold towels & ingesting ice	Ingesting 14 g/kg of ice while wearing cold towels 30 min	33	50	Cycle time trial of 46.4 km	PPO	0.70
Siegel *et al.* (2012)	k = 8 males	Ice slurry + CWI	Ingesting 7.5 g/kg of ice within 30 min + CWI for 30 min	34	52	Running till exhaustion	Running time to exhaustion	0.005+ <0.001
Skein *et al.* (2012)	k = 10 males	CWI & ice towels over shoulder	15 & 5 min	31	33	Intermittent sprint protocol for 50 min	Sprint time	0.08
Tyler *et al.* (2011)	k = 8 males	Cooling collar	N/a	32	53	Treadmill running at 70% of VO_{2max} until exhaustion	Running time to exhaustion	0.01
Uckert *et al.* (2007)	k = 20 males	Cooling vest	20 min	31	50	Incremental treadmill test	Running time to exhaustion	<0.001

& = indicates combinations within a cooling intervention; + = indicates additional cooling intervention within one study; PPO = peak power output; CWI = cold water immersion; N/a = not available, RM = repetition maximum; VO_{2max} = maximal oxygen uptake; W_{max} = maximal power output; HI = high intensity, LI = low intensity.

To test the hypothesis that external pre-cooling had an enhancing effect on performance parameters, an overall meta-analysis was conducted. This calculation showed that external pre-cooling techniques had a moderate but statistical significant effect on performance output compared to non-cooling strategies (Hedges' g = 0.49 [95% CI: 0.33 to 0.64]), which can be observed in **Figure 4**. The observed heterogeneity was high and statistically significant (Q = 77.0; df(Q) = 22; $p < 0.001$; $I^2 = 71.4\%$) suggesting that about 71.4% of the variance on observed effects reflects variance in true effects. The remaining 28.6% can be attributed to random or sampling error and would probably disappear in case of very large sample sizes. The 95% prediction interval, indicating in which range the effect size in most populations will fall, ranged from −0.17 to 1.14 Hedges' g. To assess the risk for publication bias in this overall meta-analysis, a classic fail-safe N test was conducted and showed that 729 studies would be needed to bring *p*-value to >0.05. In addition, the Duval and Tweedie's trim and fill method revealed that only two small studies were missing to obtain funnel plot symmetry (**Figure 5**). If these two studies would be considered in the meta-analysis, the

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Bogerd et al., 2010	1.202	0.337	0.113	0.542	1.862	3.569	0.000
Brade et al., 2014	0.226	0.211	0.045	-0.188	0.640	1.071	0.284
Castle et al., 2006	0.297	0.123	0.015	0.056	0.538	2.413	0.016
Duffield et al., 2007	0.228	0.237	0.056	-0.236	0.693	0.963	0.335
Duffield et al., 2009	1.129	0.346	0.119	0.452	1.806	3.267	0.001
Duffield et al., 2010	0.696	0.278	0.077	0.151	1.242	2.502	0.012
Duffield et al., 2011	0.382	0.254	0.065	-0.117	0.881	1.501	0.133
Faulkner et al., 2015	0.274	0.132	0.017	0.015	0.533	2.070	0.038
Galoza et al., 2011	0.984	0.504	0.254	-0.003	1.971	1.954	0.051
Gonzales et al., 2014	0.322	0.133	0.018	0.061	0.584	2.419	0.016
James et al., 2015_High intensity	0.168	0.155	0.024	-0.136	0.473	1.085	0.278
James et al., 2015_Low intensity	0.230	0.157	0.025	-0.077	0.537	1.467	0.142
Minett et al., 2011	0.764	0.260	0.068	0.254	1.274	2.938	0.003
Minett et al., 2012a	0.481	0.150	0.023	0.186	0.776	3.198	0.001
Minett et al., 2012b	-0.046	0.224	0.050	-0.485	0.393	-0.206	0.837
Morrison et al., 2014	0.889	0.272	0.074	0.356	1.421	3.270	0.001
Quod et al., 2008	0.876	0.331	0.109	0.228	1.524	2.650	0.008
Randall et al., 2015_packs	0.566	0.180	0.032	0.213	0.919	3.143	0.002
Randall et al., 2015_vests	0.334	0.277	0.076	-0.208	0.876	1.209	0.227
Siegel et al., 2011	1.345	0.356	0.127	0.646	2.043	3.772	0.000
Skein et al., 2012	-0.547	0.314	0.099	-1.162	0.069	-1.742	0.082
Tyler et al., 2011	0.352	0.146	0.021	0.066	0.638	2.412	0.016
Ueckert et al., 2007	1.081	0.123	0.015	0.841	1.322	8.812	0.000
Overall weighted effect	0.485	0.080	0.006	0.328	0.641	6.067	0.000

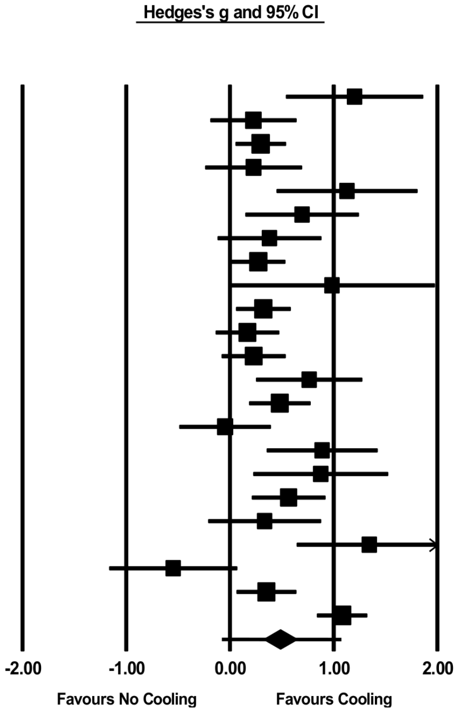

Figure 4. Forest plot of the meta-analysis illustrating the overall weighted effect of external cooling versus no cooling on performance parameters (The diamond on the bottom of the forest-plot represents the overall weighted estimate while the horizontal line through the diamond represents the 95% prediction interval).

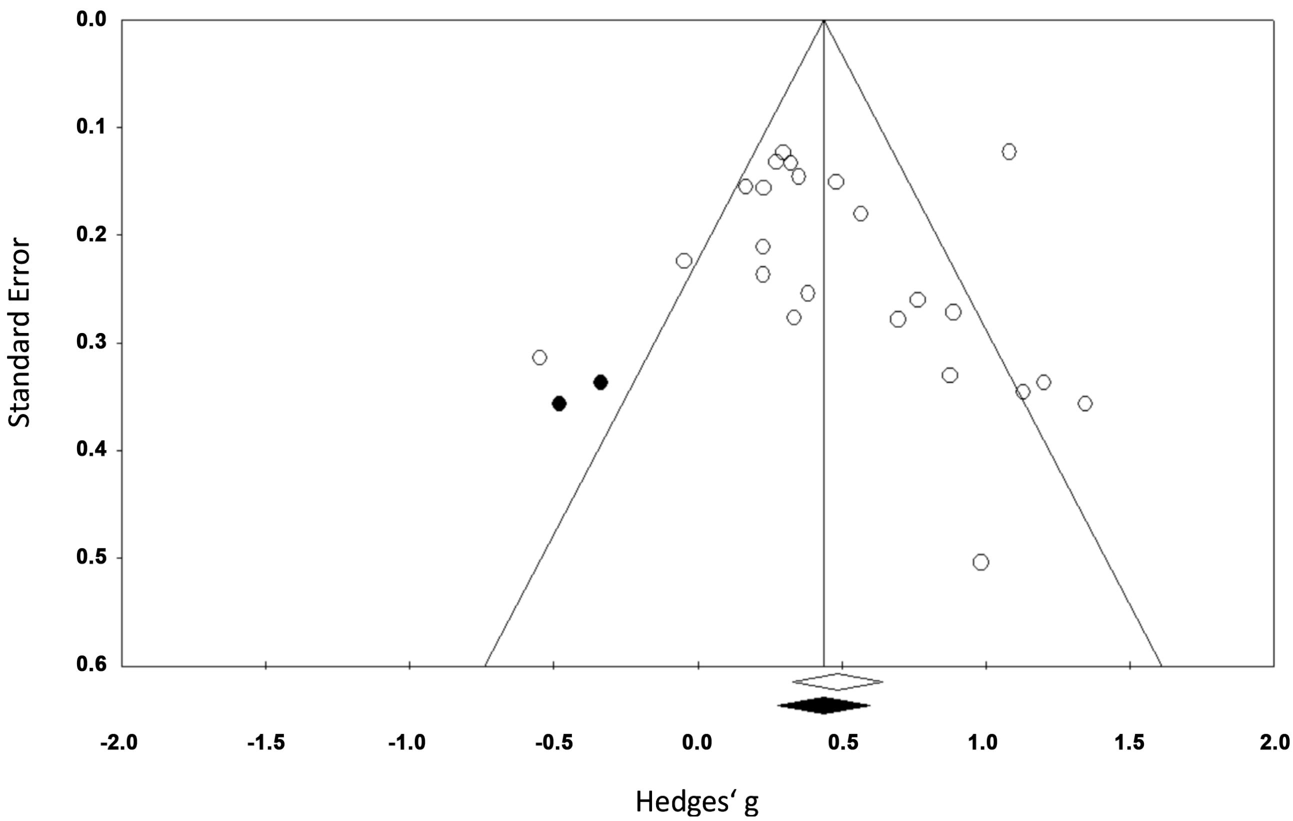

Figure 5. Funnel plot of the included studies using external-cooling strategies (The white diamond indicates the actual effect size while the black diamond indicates the adjusted effect size after adding the k = 2 missing studies).

overall weighted effect-size would yield an adjusted value of Hedges' g = 0.43 [95% CI: 0.28 to 0.58]).

In an effort to explain a part of the observed high heterogeneity in this overall meta-analysis, different subgroup meta-analyses were conducted by stratifying studies based on their type of exercise protocols (cycling, running and functional strength) and outcomes (cycle time to exhaustion, cycle time to finish, power output, running distance, running time, running time to exhaustion, sprint time, running speed and lifted weight). Pre-cooling was effective for enhancing performance characteristics in humans for both cycling (Hedges' g = 0.53, [95% CI: 0.26 to 0.80]; Q = 14.7, df(Q) = 7, $p = 0.037$; $I^2 = 52.5\%$) and running (Hedges' g = 0.45, [95% CI: 0.25 to 0.65]; Q = 59.9, df(Q) = 13; $p < 0.001$; $I^2 = 78.3\%$) exercises.

Pre-cooling had very strong, positive and statistical significant effects on cycle time to exhaustion (Hedges' g = 1.02; [95% CI = 0.53 to 1.51]), cycling time to finish (Hedges' g = 0.88; [95% CI: 0.23 to 1.52]) and running time to exhaustion (Hedges' g = 0.82; [95% CI: 0.53 to 1.11]), while low respectively moderate, positive and statistical significant effects of pre-cooling were observed on PPO (Hedges' g = 0.33; [95% CI: 0.11 to 0.55]), running distance (Hedges' g = 0.54; [95% CI: 0.28 to 0.80]) and running time (Hedges' g = 0.48; [95% CI: 0.08 to 0.88]). In these subgroups heterogeneity disappeared except for the "running time to exhaustion" subgroup where heterogeneity remained high (Q = 17.0, df(Q) = 2, $p < 0.001$; $I^2 = 88.2$). External pre-cooling had no main effect on sprint time (Hedges' g = −0.55; [95% CI: −1.16 to 0.07]), running speed (Hedges' g = 0.15; [95% CI: −0.04 to 0.35]) and lifted weight (Hedges' g = 0.98; [95% CI: −0.003 to 1.97]).

3.4. Internal-Cooling vs. Non-Cooling Strategies

Seven studies revealed the effect of internal pre-cooling on performance parameters [15] [28] [29] [39] [43] [55] [58] with one study investigating the effect on performance using a 70 min repeated cycling sprint protocol [39], one study using an endurance swimming task [43], two studies using endurance running [15] [55] and three studies using endurance cycling tasks [28] [29] [58]. Four studies examined the effects of ingesting ice [15] [29] [39] [55] on performance while three studies used cold water [28] [43] [58] as a cooling intervention. The overall weighted mean estimate showed that internal cooling has a moderate and positive, albeit no statistical significant effect compared to the control condition on performance parameters (Hedges' g = 0.55; [95% CI: −0.01 to 1.11]) (**Figure 6**). The 95% prediction interval indicating the range of possible true effect sizes in most populations ranged from −1.38 to 2.48 Hedges' g. The observed heterogeneity was high and statistically significant (Q = 56.38, df (Q) = 7; $p < 0.001$; $I^2 = 87.5\%$). The heterogeneity could not be explained with a subgroup analysis, according to cooling method, exercise task or performance outcome, because meaningful grouping was not plausible.

3.5. Mixed-Method Internal and External Cooling vs. Non-Cooling Strategies

Five studies examined the effects of mixed-method internal and external cooling versus non-cooling strategies on PPO and performance times [30] [39] [44] [45] [46]. Four studies investigated the effect of pre-cooling prior to a cycle sprint [39] [45] or endurance cycle trial [30] [46] while one study investigated the effect of pre-cooling on repeated sprint running times [44]. The overall weighted mean effect size between mixed method pre-cooling and the control group was very low and statistically not significant (Hedges' g = 0.07; [95%CI: −0.06 to 0.22]). Heterogeneity was low (I^2 = 17.41%) and not significant (Q = 4.84; df(Q) = 4; p = 0.30). The 95% prediction interval ranged from −0.24 to 0.39 (see **Figure 7**). These results indicate that mixed-method pre-cooling is not superior compared to the non-cooling control group for enhancing performance. Subgroup analyses or meta-regression was not plausible to conduct due to the low number of studies included in this analysis.

4. Discussion

The aim of this systematic review and meta-analysis was to evaluate the effects of

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Brade et al., 2014	-0.224	0.211	0.045	-0.638	0.189	-1.064	0.287
Byrne et al., 2011	0.478	0.239	0.057	0.009	0.947	1.999	0.046
Hue et al., 2013	0.101	0.234	0.055	-0.357	0.560	0.433	0.665
Ihsan et al., 2010	0.413	0.269	0.072	-0.113	0.939	1.538	0.124
James et al., 2015_High intensity	0.185	0.534	0.285	-0.863	1.232	0.346	0.730
James et al., 2015_Low intensity	0.252	0.535	0.287	-0.798	1.301	0.470	0.638
Lee et al., 2008	2.484	0.311	0.097	1.874	3.094	7.981	0.000
Siegel et al., 2012	0.668	0.236	0.056	0.205	1.131	2.830	0.005
Overall weighted effect	0.551	0.285	0.081	-0.009	1.110	1.930	0.054

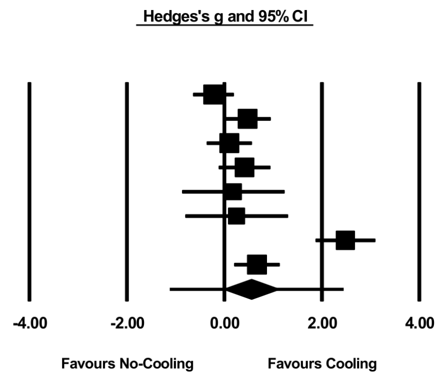

Figure 6. Forest plot of the meta-analysis illustrating the overall weighted effect of internal cooling versus no cooling on performance parameters (The diamond on the bottom of the forest-plot represents the overall weighted estimate while the horizontal line through the diamond represents the 95% prediction interval).

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Brade et al., 2014	0.258	0.212	0.045	-0.158	0.673	1.215	0.224
Brade et al., 2013a	-0.105	0.225	0.050	-0.546	0.335	-0.468	0.640
Brade et al., 2013b	-0.117	0.225	0.051	-0.558	0.324	-0.520	0.603
Ross et al., 2011	0.282	0.139	0.019	0.009	0.555	2.022	0.043
Ross et al., 2012	0.025	0.066	0.004	-0.104	0.154	0.377	0.706
Overall weighted effect	0.075	0.069	0.005	-0.061	0.211	1.078	0.281

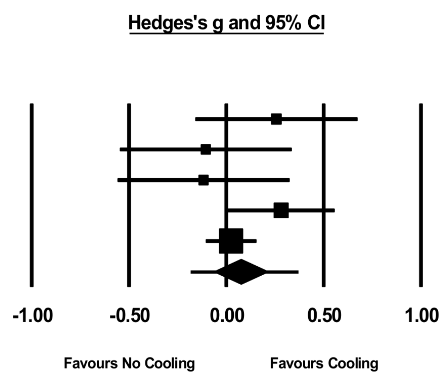

Figure 7. Forest plot of the meta-analysis illustrating the overall weighted effect of mixed-method cooling versus no cooling on performance parameters (The diamond on the bottom of the forest-plot represents the overall weighted estimate while the horizontal line through the diamond represents the 95% prediction interval).

pre-cooling (external cooling, internal cooling and mixed-method cooling) vs. non-cooling strategies on different performance parameters in hot and humid environmental conditions. The analysis demonstrated that, prior to exercise tasks, external cooling methods had a significant better effect on performance parameters compared to non-cooling strategies. However, internal cooling and mixed method cooling strategies were not superior compared to non-cooling strategies to enhance performance.

4.1. External-Cooling vs. Non-Cooling Strategies

The overall weighted mean difference revealed a significant ($p < 0.001$) effect of pre-exercise external cooling applications on the performance output compared to non-cooling strategies. The observed effect size for this analysis was small (Hedges' g: 0.49). The strongest effect of pre-cooling was observed for cycling performance (Hedges' g: 0.53; $p < 0.001$), primarily cycle time to exhaustion ($p < 0.001$) and cycling time to finish ($p = 0.008$) under hot (ranging from 29 to 34˚C) and humid (ranging from 41 to 80%) conditions. Only one study in the subgroup analysis showed a non-significant result for external pre-cooling on cycle performance [39]. The main difference to the other studies was, that Brade *et al.* (2014) did use a repeated sprint protocol with a 10 min break between the sets. Each set comprised of 120 maximal sprints at varying intensities, which made (self-) pacing very difficult in this protocol. These findings suggest that vasoconstriction occurred, preventing heat exchange from the body-core to the surroundings (cooling vest), resulting in non-affected core temperature changes. Similar observations were already described in previously published studies [24] [59].

Pre-cooling demonstrated to be overall significant effective for running tasks ($p < 0.001$). Open-end exercise tests, like the determination of total running distance and running time to exhaustion seem to be primarily positive affected from pre-cooling ($p < 0.001$ and $p = 0.003$), especially under hot (ranging from 31˚C to 35˚C) and humid (ranging from 30% to 53%) conditions. However, the subgroup analysis demonstrated that it was ineffective to enhance running speed and sprint times and weight lifting. It has already been reported that decreased muscle temperature from excessive cooling can negatively influence voluntary force production and sprint performance [57]. Decreased tissue temperature has been shown to reduce nerve conduction velocity, muscle force production and muscular power [60] [61] [62]. These observations are in line with the findings of Galoza *et al.* (2011), demonstrating that external pre-cooling failed to significantly affect weight lifting activity in the biceps brachii muscle compared to a non-cooling strategy [40]. However, it has to be taken into account that only one study was included in the subgroup analysis of the present meta-analysis for assessing sprint time and weight lifting, respectively.

The results of this meta-analysis show some evidence that external pre-cooling methods may be effective for enhancing performance parameters with combinations of external cooling methods (k = 5; Hedges' g range: 0.32 to 1.12), CWI (k = 3; Hedges' g range: 0.69 to 1.34), cooling vests (k = 2; Hedges' g range: 0.27 to 1.20) and local cooling applications (k = 3; Hedges' g range: 0.29 to 0.56) demonstrating to have the largest effect.

4.2. Internal-Cooling vs. Non-Cooling Strategies

The overall weighted effect indicated that internal pre-cooling is not effective vs. non-cooling strategies ($p = 0.05$) to enhance performance under hot and humid environmental conditions. As it can be observed in **Figure 6**, only two studies showed statistically significant effects, favouring internal cooling [15] [58]. Interestingly, these two authors investigated the effects on open-end protocols (time to exhaustion) during endurance running [15] and cycling [58]. The remaining included studies evaluated the effects on PPO [28] [29] [39] or speed factors [55] with no superior effect of pre-cooling with ice. These findings are in line with a comparable finding [32]. Other studies have already demonstrated that the effect of internal cooling is only limited. One main mechanism, which is not present after or during internal cooling methods, is the reduction of the shell temperature. This drop in temperature causes a redistribution of blood to the core, leading to a reduced heart rate [63] and a larger stroke volume [6]. However, the present study indicates that internal cooling can decrease core temperature. Reduced core temperature is well known to increase heat storage capacity [64]. However, a lower body core temperature may also reduce the participants' performance output due to central regulation mechanisms [65] because tissue temperature reductions will negatively influence the maximal loco-motor speed through reduced afferent and efferent signal transmission [66]. Muscle contractions produce heat inside the muscle, before any change in core temperature can be noticed. This muscle temperature rise increases the rate of force development of a muscle twitch with positive effects on power and speed [67] [68]. The results of this present meta-analysis are in line with comparable studies showing the efficacy of internal pre-cooling on endurance performance [32]. It has been speculated that the cooled water, while passing the oesophagus, might reduce the blood temperature in the carotid artery and this would decrease the athlete's brain temperature, leading to enhanced performance output in the heat [69] [70]. However, most research, concentrating on the effectiveness of internal cooling on performance tries to explain the mechanisms via changes in core temperature. More mechanistic (e.g. investigation of brain and muscle temperature or cutaneous vascular conductance) insights are needed to further elucidate the potential mechanisms behind this very practical pre-cooling method.

4.3. Mixed-Method Internal and External Cooling vs. Non-Cooling Strategies

This meta-analysis could not demonstrate a statistically significant ($p = 0.28$)

overall weighted effect of mixed-method pre-cooling on performance output. However, it has to be mentioned, that the included studies used acclimatization periods prior to the pre-cooling method (for the experimental and control group). Acclimatization to hot environmental conditions has been demonstrated to be a key component for reducing the negative effects of heat strain [19]. Brade *et al.* (2013) concluded that pre-cooling alone is unnecessary if athletes are heat acclimated [44]. Therefore, an increase of the heat storage capacity seems to be more effective with acclimatisation to the heat than pre-cooling the body core and shell. Acclimatisation to the heat has various physiological advantages to enhance performance. One main factor is that the increase in core and skin temperature is attenuated through increased sweat rates [71]. Evaporative heat loss is the most effective way to release heat from the body [10]. Furthermore, the increased heart rate is also attenuated because of the increasing stroke volume during acclimatisation [71]. This might be one explanation why a positive effect of pre-cooling can rather be seen in aerobic exercises than in anaerobic exercise or power outputs. Muscle power depends strongly on the actual muscle temperature. Published data have already demonstrated that an increase in muscle temperature (through immersion in hot water) leads to higher vertical jump performances [72]. A similar positive observation has been demonstrated after warm water immersion prior to intensive cycling exercises on PPO [72]. As mixed-method cooling aims to lower tissue temperature it might be possible that cold has a negative effect on dynamic force production, as described earlier [73].

4.4. Limitations and Future Research

Figure 2 and **Figure 3** depict that the included studies had a high or unknown risk of bias. Both the implementation and the description of the random sequence generation and the procedure of the allocation concealment would have already helped to minimize the risk of a selection bias. The blinding of participants and personnel is impossible when working with cold applications. Therefore, the high risk of performance bias is not surprising in the analysed articles. The occurrence of both detection and other bias remained unclear. Only the risk for reporting bias seems to be mainly low with only three unclear rated studies. Due to these observations, it has to be taken into account, that the results of this meta-analysis can both either underestimate or overestimate the true intervention effect of pre-cooling on performance parameters. A previously published meta-analysis in the field of cooling reported already limitations according to possibly biased results of the included studies [74]. Considering this, the authors of the current study implemented the prediction intervals in the forest plots to give the reader the possibility to observe the possible true effect sizes for each outcome in most populations. The included studies showed a broad variety of both endurance and sprint protocols, making meaningful subgroup analysis difficult or impossible (internal cooling and mixed-method cooling). Also the cooling protocols showed broad variety making direct comparisons difficult.

Furthermore, the included studies used primarily at least well-trained, male participants for their investigation of pre-cooling. It is still unclear, if the effects of pre-cooling, obtained from the current observations, can be extrapolated to male, untrained or even female participants. Future research is strongly advised to control for the systematic error (especially by eliminating selection bias, detection bias and other bias). Although the effects of pre-cooling on performance are more relevant in field settings than in laboratory settings, researchers should also take into account that these results can be hardly replicated or even compared to each other.

5. Conclusion

Based on the results of this meta-analysis, external pre-exercise cooling appears to be an effective intervention to enhance performance in hot (between 29˚C and 34˚C) and humid (41% to 80%) conditions. Endurance running and cycling tasks were primarily affected from external pre-cooling. Combinations of external cooling applications, CWI and wearing cooling vests demonstrated to have the largest effects. Internal and mixed-method cooling demonstrated to have no main effect on performance enhancement, although internal cooling might have a significant positive effect on both cycling and running endurance tasks. However, it has to be considered that the main outcome parameter for internal and mixed-method pre-cooling was PPO. The low number of studies made an evaluation of the possible effects of internal and mixed-method pre-cooling on endurance performance impossible. The high and unclear risk of bias of the included studies has to be taken into account when using the current results, although the risk for publication bias was very low.

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Conflict of Interest Statement

The authors declare no conflict of interest.

Author Contributions

Conceived and designed the experiments: EH PC RC JT. Data extraction and quality assessment: EH RS TD JT. Risk of bias assessment: EH RS RC. Analysis of the data: EH JT. Wrote the paper: EH PC JT RC. Read and approved final version of manuscript: EH RS PC RC TD JT.

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Supporting Information

PRISMA 2009 Checklist

Section/topic	#	Checklist item	Reported on page #
TITLE			
Title	1	Identify the report as a systematic review, meta-analysis, or both.	1
ABSTRACT			
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known.	3-4
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS).	4-5
METHODS			
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number.	-
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale.	4-5
Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.	5
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	5, Fig 1
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	4-5
Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	5-6
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	4-5
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	5-6
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means).	6-7
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I^2) for each meta-analysis.	6-7

PRISMA 2009 Checklist

Section/topic	#	Checklist item	Reported on page #
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	5-6
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	6-7
RESULTS			
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	Fig 1
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	Table 1
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12).	Fig 2
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot.	Figs 4-7
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	Figs 4-7
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see Item 15).	Fig 3
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]).	16-19, Fig 5
DISCUSSION			
Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers).	20-23
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias).	24-25
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	25
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.	-

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