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Precooling and percooling (cooling during exercise) both improve performance in the heat: A meta-analytical review

Article

Precooling and Percooling (cooling during exercise) both improve performance in the heat: A Meta-Analytical Review

RUNNING TITLE: Precooling *versus* Percooling

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ABSTRACT

Background: Exercise increases core body temperature (Tc), which is necessary to optimise physiological processes. However, excessive increase in Tc may impair performance and places subjects at risk for the development of heat-related illnesses. Cooling is an effective strategy to attenuate the increase in Tc. This meta-analysis compares the effects of cooling *before* (precooling) and *during* exercise (percooling) on performance and physiological outcomes.

Methods:A computerized literature search, citation tracking and hand search was performed up to May 2013. Twenty-eight studies met the inclusion criteria, which were trials that examined the effects of cooling strategies on exercise performance in men, whilst exercise was performed in the heat (>30°C). Twenty studies used precooling, while eight studies used percooling.

Results: Overall effect of pre- and percooling interventions on exercise performance was +6.7±0.9% (effect size (ES)=0.43). We found a comparable effect (p=0.82) of precooling (+5.7±1.0% (ES=0.44)) and percooling (+9.9±1.9% (ES=0.40)) to improve exercise performance. A lower finishing Tc was found in precooling (38.9°C) compared to control condition (39.1°C, p=0.03), whilst Tc was comparable between conditions in percooling studies. No correlation between Tc and performance was found. We found significant differences between cooling strategies, with combination of multiple techniques being most effective for precooling (P<0.01) and ice vest for percooling (P=0.02).

Conclusion: Cooling can significantly improve exercise performance in the heat. We found a comparable effect size for precooling and percooling on exercise performance, while the type of cooling technique importantly impacts the effects. Precooling lowered the finishing core temperature, whilst there was no correlation between Tc and performance.

INTRODUCTION

Paragraph 1. Excessively elevated core body temperature (Tc), arising from a disbalance between heat production and heat loss during prolonged exercise, has a negative impact on physiological functions and exercise performance (1, 2). Moreover, an elevated Tc can even lead to the development of severe heat illnesses, such as heat stroke (2). The relevance of attenuating the increase in Tc during exercise is highlighted by the organization of future major sport events in hot and/or humid climatic conditions (e.g. Olympic Games of Rio de Janeiro 2016 and the FIFA World Cup in Brazil 2014 and Qatar 2022). Moreover, the level of performance decrement progressively increases with a rise in environmental heat stress (3). Strategies that can prevent excessive heat storage during exercise in the heat, and consequently a reduction in exercise performance, are therefore of high interest.

Paragraph 2. Cooling can be applied prior to (*pre*cooling) or during (*per*cooling) exercise to attenuate the increase in Tc and improve exercise performance. Existing reviews and meta-analyses showed that precooling can effectively enhance exercise performance (4-7). A substantially lower number of studies focused on cooling strategies applied *during* exercise: percooling. Performance benefits of precooling normally decrease after 20-25 minutes of exercise (8). Therefore, the use of cooling techniques *during* an exercise bout, especially when involving endurance exercise, may elongate the duration of the beneficial effects of the cooling intervention on exercise performance. In addition to the larger 'window of opportunity' to cool the athlete, the level of thermal strain is higher during exercise compared to resting conditions (9). This suggests that cooling during exercise has a large potential in clinical practice to prevent significant thermal strain and maintain exercise performance. These cooling strategies are referred to as percooling, derived from the Latin word *per* meaning 'during'. To date, relatively little is known about the impact of percooling on exercise performance, or examined the hypothesis that percooling is more effective than precooling (10).

Paragraph 3. The purpose of this meta-analytical review is to compare the effects of precooling and percooling on exercise performance and on relevant thermophysiological outcomes (i.e. core body temperature, skin temperature, heart rate, rate of perceived exertion) in healthy volunteers under hot climatic conditions. Furthermore, the effects of pre- and percooling on performance may vary between cooling techniques (cooling vests, cold water immersion, cold water ingestion, cooling packs, and mixed method cooling) (4-6, 11-13). Better insight into these techniques is necessary to identify the 'best practice' cooling technique to improve exercise performance under hot thermal conditions. Therefore, the second aim of this study is to review current literature on this topic and determine differences between cooling techniques.

METHODS

Search strategy

Paragraph 4. We searched Pubmed and Web of Science. Ten mesh terms and keywords ('exercise', 'cooling', 'performance', 'during exercise', 'precooling', 'effects', 'ice slurry ingestion', 'cooling vest', 'cold water immersion', and 'cold water ingestion') were combined by Boolean logic (AND) and the results were limited to human subjects and articles written in English. Each database was searched from their earliest available article up to May 7, 2013. We also searched in the reference list of all incoming articles.

Study selection

Paragraph 5. Selection of publications for inclusion in this meta-analysis was based on the following criteria. First, only studies applying a cooling intervention before (‘precooling’) or during exercise (‘percooling’) and in a crossover design were selected. Moreover, only studies performed in hot ambient conditions with ambient temperatures ≥30°C were included. Secondly, only study populations comprising male adults, or studies comprising both sexes where data of male subjects was reported separately were included to avoid any potential impact of the menstrual cycle on study results. Furthermore, only studies reporting at least one outcome parameter associated with cycling or running exercise performance (e.g. finish time, completed distance, time to exhaustion, power output, etc.) were included in this meta-analysis. Studies that merely evaluated the effects of cooling on physiological outcomes (heart rate, blood lactate levels) were excluded. The first author was responsible for the study selection. After the selection process, all studies were discussed with two co-authors. In case of disagreement about the inclusion of a study, a voting process was used to determine if a study was included or not. Figure 1 provides a flow chart of our literature search.

Study classification

Paragraph 6. After inclusion, studies were classified into groups based on the following criteria. For our first aim, studies were classified based on the type of cooling (precooling *versus* percooling). For our second aim, studies were classified according to their cooling strategy: 1) cooling vest (ice vests and evaporative cooling vests), 2) cold water immersion, 3) cold water ingestion and/or ice slurry ingestion, 4) cooling packs, and 5) mixed method cooling (combined application of two or more cooling techniques). Furthermore, studies that compared multiple cooling intervention trials with the same control condition, were included more than once.

Effect size assessment

Paragraph 7. For all studies that were included, standardized mean differences (effect size in Hedge's g) and 95% confidence intervals were calculated for continuous outcomes using the Cochrane Collaboration's software Review Manager 5.1.0 (Cochrane IMS, Melbourne, Australia). Statistical analyses were also performed using this software, with the significance level set at $p<0.05$. The calculations in this program were based on the difference in outcome between the intervention and the control condition. To calculate the standard error, we needed the exact p-value (for calculation of the t-value). When the p-value was not provided, we contacted the corresponding author. However, if this information could not be provided or the author did not respond, we used $p=0.049$ and $p=0.051$ for $P<0.05$ and $P>0.05$ respectively. This progressive approach avoids an overestimation of the effect of cooling. However, as it may also cause a selection bias, we performed a sub-analysis including only studies that provided the exact p-values.

Negative effects of cooling were indicated with a minus sign. Data for all single studies and weighted average values were presented as mean±SD. The interpretation of the effect size (ES) was based on the following scale: 0-0.19 = negligible effect, 0.20-0.49 = small effect, 0.50-0.79 = moderate effect and ≥0.80 = large effect (14). The presence of publication bias was established by evaluating Begg's funnel plot asymmetry (15) and the Egger's linear regression test (16), in which $p<0.05$ was considered significant (17).

Physiological parameters

Paragraph 8. We included core temperature (Tc), skin temperature (Tskin) and heart rate (HR) in this meta analysis. Data was extracted from text, tables or figures (using GetData Graph Digitizer software v2.26). The effect of the cooling intervention was calculated by subtracting data of the cooling condition from the control condition (ΔTc, ΔTskin and ΔHR). Correlations between the change in physiological responses and the relative change in performance were calculated using SPSS 20.0 (SPSS, Chicago, USA) and the level of significance was set at $p<0.05$. Student's paired t-tests were used to examine differences in finishing Tc, Tskin and HR between the cooling and the control condition.

RESULTS

Included studies

Paragraph 9. A total of 28 manuscripts that met our inclusion criteria (11, 12, 18-43) were identified. Some of these studies compared multiple cooling interventions and were therefore included more than once, which resulted in a total of 36 studies with a total number of 323 subjects. Characteristics of the included studies are summarized in the online supplementary Table 1. The average sample size was 9, while the largest study was based on 20 subjects. The weighted average improvement of the cooling strategies on exercise performance in all studies was 6.7±0.9% and the weighted average ES was 0.43±0.06. A funnel plot of all studies demonstrates the presence of publication bias due to asymmetry (Figure 2). The publication bias was confirmed by a statistical significant Egger's test ($p<0.01$) and a significant Begg's funnel plot ($p=0.01$). The sub-analysis, in which the studies with exact p-values were included only, did not alter the outcomes of the original analysis. Therefore, only data from the initial analysis are provided.

Precooling *versus* percooling

Paragraph 10. Twenty-seven studies applied a precooling intervention and nine studies applied percooling (Figure 3). The weighted average exercise performance improvement of precooling was 5.7±0.9% (ES=0.44) and for percooling interventions 9.9±1.9% (ES=0.40). We found no significant difference in effect size for both types of cooling on exercise performance in the heat (p=0.82).

Effects on physiological parameters

Paragraph 11. Table 1 shows an overview of the (change in) physiological parameters during the control and cooling condition. We found a significantly lower finishing Tc in the precooling (38.9°C) condition compared to control (39.1°C, p=0.03), whilst Tc was comparable for the percooling studies. Tskin and HR did not differ between the cooling and control condition for both precooling and percooling (all p-values>0.05). Furthermore, no correlations were found between measures of performance and ΔTc, ΔTskin and ΔHR for precooling, percooling and the pooled set of cooling studies (all p-values>0.05).

Table 1. Individual study data regarding the physiological responses, in which Δ were calculated as cooling minus control condition.

Precooling		**Tc max control**	**Tc max cooling**	**Δ Tc max**	**Tskin max control**	**Tskin max cooling**	**Δ Tskin max**	**HR max control**	**HR max cooling**	**Δ HR max**	**Performance (%)**
Cooling packs	Castle et al. 2006c	39.1	38.4	-0.7	36.9	36.4	-0.5	179	181	2	4.3
	Minett et al. 2011a	39.1	39.1	0	34.0	34.2	0.2	173	175	2	4.3
	Weighted average	39.1	38.8	-0.4	35.5	35.3	-0.1	176	178	2	4.3
Cooling vests	Arngrimsson et al. 2004	39.8	39.6	-0.2	34.2	34.5	0.3	195	195	0	1.3
	Castle et al. 2006a	39.1	38.9	-0.2	36.9	36.6	-0.3	179	184	5	1.5
	Duffield et al 2003	38.8	38.7	-0.1	34.0	33.6	-0.4	N.A	N.A	N.A	2.4
	Duffield et al. 2007a	39.6	39.2	-0.4	34.4	34.4	0	182	187	5	1.3
	Quod et al. 2008a	39.6	39.7	0.1	34.6	34.5	-0.1	193	193	0	1.5
	Ückert et al. 2007	38.8	38.4	-0.4	35.6	35.1	-0.5	192	190	-2	7.3
	Weighted average	39.3	39.1	-0.2	35.0	34.8	-0.2	188	190	2	3.4
Cold water ingestion	Burdon et al. 2013	38.7	38.7	0.0	33.4	33.3	-0.1	165	168	3	10.5
	Byrne et al. 2011	38.6	38.1	-0.5	35.4	35.1	-0.3	190	189	-1	2.9
	Ihsan et al. 2010	38.8	39.1	0.3	35.6	35.8	0.2	N.A	N.A	N.A	6.9
	Siegel et al. 2012a	39.5	39.8	0.3	35.7	35.5	-0.2	188	189	1	12.8
	Stanley et al. 2010	39.1	39.0	-0.1	N.A	N.A	N.A	191	191	0	1.9
	Stevens et al. 2013	39.0	38.2	-0.8	N.A	N.A	N.A	N.A	N.A	N.A	2.8
	Weighted average	39.0	38.8	-0.1	35.0	34.9	-0.1	184	184	1	6.3
Mixed method cooling	Cotter et al. 2000	38.9	38.5	-0.4	35.9	35.1	-0.8	178	177	-1	15.2
	Duffield et al. 2007b	39.6	39.0	-0.6	34.4	34.0	-0.4	182	187	5	8.3
	Duffield et al. 2009	39.3	38.8	-0.5	N.A	N.A	N.A	162	146	-16	7.7
	Duffield et al. 2013	39.0	38.9	-0.1	34.6	34.8	0.2	182	186	4	3.0
	Minett et al. 2011b	39.1	39.0	-0.1	34.0	34.1	0.1	173	170	-3	5.2
	Minett et al. 2011c	39.1	38.7	-0.4	34.0	33.1	-0.9	173	169	-4	9.5
	Minett et al. 2012	39.1	38.7	-0.4	33.9	33.1	-0.8	178	170	-8	4.7
	Quod et al. 2008b	39.6	39.5	-0.1	34.6	33.8	-0.8	193	192	-1	4.0
	Weighted average	39.1	38.9	-0.3	34.5	34.0	-0.5	178	175	-3	7.3
Cold water immersion	Castle et al. 2006b	39.1	38.8	-0.3	36.9	34.5	-2.4	179	175	-4	-0.5
	Duffield et al. 2010	39.0	38.9	-0.1	35.7	35.5	-0.2	178	183	5	7.2
	Kay et al. 1999	38.8	38.5	-0.3	34.7	33.6	-1.1	178	177	-1	6.0
	Siegel et al. 2012b	39.5	39.5	0	35.7	35.3	-0.4	188	190	2	21.6
	Skein et al. 2012	38.9	38.7	-0.2	31.5	33.1	1.6	180	182	2	2.4
	Weighted average	39.1	38.9	-0.2	34.9	34.4	-0.5	181	181	1	6.5
Total precooling	**Weighted average**	**39.1**	**38.9**	**-0.2**	**34.9**	**34.5**	**-0.3**	**181**	**181**	**0**	**5.7**
	Students T-test	**0.03**			**0.34**			**0.94**			

Percooling		**Tc max control**	**Tc max cooling**	**Δ Tc max**	**Tskin max control**	**Tskin max cooling**	**Δ Tskin max**	**HR max control**	**HR max cooling**	**Δ HR max**	**Performance (%)**
Cooling packs	Hsu et al. 2005	38.4	38.1	-0.3	N.A	N.A	N.A	159	161	2	6.6
	Minetti et al. 2011	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A	5.4
	Scheadler et al. 2013	39.2	39.4	0.2	N.A	N.A	N.A	178	178	0	-11.6
	Tyler et al. 2010a	39.3	39.1	-0.1	35.0	35.6	0.6	186	188	2	5.1
	Tyler et al. 2010b	38.3	38.4	0.1	35.8	26.1	-9.7	187	187	0	1.9
	Tyler et al. 2011a	39.2	39.7	0.5	35.6	27.6	-8	181	178	-3	7.0
	Tyler et al. 2011b	38.9	38.9	0	34.4	35.3	0.9	185	186	1	13.0
	Average	38.9	38.9	0.1	35.2	31.2	-4.1	179	180	0	3.9
Cooling vest	Luomala et al. 2012	38.9	39.1	0.2	34.5	34.7	0.2	174	178	4	20.4
	Average	38.9	39.1	0.2	34.5	34.7	0.2	174	178	4	20.4
Cold water ingestion	Mündel et al. 2006	38.7	38.4	-0.3	N.A	N.A	N.A	170	165	-5	12.7
	Average	38.7	38.4	-0.3	N.A	N.A	N.A	170	165	-5	12.7
Total percooling	**Average**	**38.9**	**38.9**	**0.0**	**35.1**	**31.9**	**-3.2**	**178**	**178**	**0**	**7.0**
	Students T-test	**0.91**			**0.16**			**0.98**			
Total all studies	**Average**	**39.1**	**38.9**	**-0.2**	**34.9**	**34.1**	**-0.8**	**180**	**180**	**0**	**5.6**
	Students T-test	**0.08**			**0.08**			**0.97**			

Tc = core body temperature; **Tskin** = skin temperature; **HR** = heart rate; **N.A** = not available; **max** = at the end of the exercise protocol

Different cooling techniques

Paragraph 12. *Precooling.* We found that the effect of the different cooling strategies on exercise performance significantly differed across precooling techniques (p<0.001). Mixed method cooling (+7.3%, ES=0.72, Figure 3) demonstrated a significantly larger effect size (p<0.01) compared to cold water immersion (+6.5%, ES=0.49), cold water/ice slurry ingestion (+6.3%, ES= 0.40), cooling packs (+4.3%, ES= 0.40), and cooling vests (+3.4%, ES= 0.19) (Table 2).

Paragraph 13. *Percooling.* For percooling studies, three different cooling techniques were identified; ice vest, cold water ingestion and cooling packs (Table 2). We found a significant difference in effect size between the 3 percooling techniques in our meta-analysis (p=0.01). Wearing an ice vest during exercise (+21.5%, ES= 4.64) was significantly more effective in improving exercise performance compared to cold water ingestion (+11%, ES= 1.75) and cooling packs (+8.4%, ES= 0.39) (p=0.02, Table 2).

Table 2. Overview of subtotal effect sizes ± 95% CI of different cooling techniques for the precooling and percooling interventions.

	Number of studies	Precooling	Number of studies	Percooling
Cooling vest	6	0.19 (0.10-0.28)	1	4.64 (0.96-8.32)
Cold water immersion	5	0.49 (0.09-0.90)	-	Not available
Cold water ingestion	6	0.40 (0.17-0.62)	1	1.75 (0.38-3.12)
Cooling packs	2	0.40 (0.10-0.71)	7	0.34 (0.09-0.58)
Mixed method cooling	8	0.72 (0.49-0.96)	-	Not available
Average effect size	27	0.44 (0.31-0.56)	9	0.40 (0.15-0.66)

DISCUSSION

Paragraph 14.

The purpose of this meta-analysis was to 1) compare the effects of precooling *versus* percooling on exercise performance and thermophysiological reponses in the heat, and 2) to identify the most effective cooling technique for improvement in exercise performance. Reviewing and analyzing data of the existing studies indicates that cooling significantly improves exercise performance, whilst the effect of cooling was similarly present between precooling and percooling. Secondly, thermophysiological (such as core and skin temperature and heart rate) outcomes did not change in response to both precooling and percooling, whilst no correlation was present between the change in thermophysiological measures and exercise performance. Thirdly, we found significant differences between *pre*cooling techniques to improve exercise performance, with the use of a mixed method of cooling being the most effective. Such an effect between different techniques was also observed for percooling, with an ice vest being the most effective strategy. Taken together, cooling prior to or during exercise in the heat improves exercise performance with evidence supporting a superior effect of mixed methods for precooling and ice vests for percooling on performance levels in athletes, whilst these performance effects are unlikely related to a lower skin or core body temperature.

Paragraph 15. Our analysis summarizes and demonstrates a significant effect of cooling interventions on exercise performance in healthy athletes under demanding thermal conditions (1, 7, 44). We extend the current knowledge by the observation that the impact of precooling and percooling on exercise performance is comparable. It is important to take note of the significant publication bias, which is demonstrated in the Funnel plot (Figure 2), suggesting that negative studies may not have been published. Although this could implicate an overestimation of the overall effect of cooling, there is still abundant evidence that cooling effectively improves exercise performance when exercise is performed in the heat. The application of pre- and percooling are therefore both recommended to improve exercise performance while exercising in hot ambient conditions.

Paragraph 16. Although our statistical analysis does not support a difference in effect size between pre- and percooling (ES = 0.44 *versus* 0.40), the variation in performance enhancement between precooling (+5.7%) and percooling (+9.9%) is large. It is believed that both cooling strategies achieve their effects through comparable underlying mechanisms. It is known that exercise leads to a significant level of thermal strain due to a large increase in heat production in the exercising muscles. Maintaining an adequate heat balance requires a significant amount of energy for heat dissipating mechanisms, such as (skin) vasodilation and sweating responses (9, 45). Percooling contributes to a higher heat storage capacity, a more efficient heat loss and may attenuate the increase in core body temperature. The attenuated increase in Tc, may prevent a decrease in exercise performance. The purpose of precooling is to lower Tc before starting the exercise, leading to an increase in heat storage capacity during exercise. It is hypothesized that the larger heat buffer, induced by precooling, enables the body to perform more work prior reaching a critical limit for Tc (13). This suggests that pre- and percooling both enhance exercise performance. Accordingly, we hypothesize that a combination of precooling and percooling may be more effective in improving exercise performance than a single cooling strategy only. To date, only one pilot study (n=9) examined this hypothesis and showed that combined pre- and percooling is superior in improving exercise performance compared to pre- or percooling alone (46). Future studies may be aimed to further explore the combined effect of pre- and percooling on exercise performance.

Paragraph 17. One important question that this meta-analysis tried to answer is whether the impact of cooling strategies can be explained through its effects on thermophysiological factors. Precooling resulted in a significantly lower finishing Tc in the cooling compared to control condition, whilst this finding was absent in percooling studies. Presumably, percooling attenuated the increase in Tc and thus increase the heat storage capacity. For this reason, athletes were able to produce more heat before terminating exercise or lowering exercise intensity, which results in performance enhancements (10, 33). Likewise, we did not find correlations between the change in physiological parameters and the improvement of performance (Figure 4). These findings suggest that a lower Tc at the end of exercise does not necessarily improve exercise performance in the heat. More likely, the cooling interventions resulted in a reduction of the rise in physiological parameters, which enabled athletes to exercise at a higher absolute amount of work resulting in an improved performance but a comparable finishing Tc, Tskin and HR (5).

Paragraph 18. None of the included studies reported any thermoregulatory problems or heat related illnesses amongst their subjects. This may imply that our body applies internal protection mechanisms to avoid reaching a critical high temperature. There are 2 common hypotheses that may explain this thermal behaviour. Firstly, as Tc becomes elevated, exercise will be terminated once critically high internal temperatures are attained, which is a safeguard that limits the potential development of dangerous heat illness (5, 6). Secondly, the rate of heat gain is detected by our body, which could anticipatorily adjust the work rate to ensure that the exercise task can be completed within the homeostatic limits of the body (5, 47). As this meta-analysis included merely information about peak Tc, we could not test which hypothesis was adopted by athletes while performing exercise in the heat. Future studies that compare the threshold- with the anticipatory-theory are recommended, so that appropriate cooling techniques can be selected accordingly.

Paragraph 19. This meta-analysis demonstrated a significant impact of the type of cooling strategy when performing precooling to enhance exercise performance. Our analysis revealed that a combination of techniques (i.e. ‘mixed method precooling’) had a significantly larger effect than individual cooling techniques (cold water/ice slurry ingestion, cooling vests, cooling packs, or cold water immersion alone). This observation is reinforced by a study which examined three precooling strategies; 1) cooling pack, 2) cooling pack + cold water immersion, and 3) cooling pack + cold water immersion + ice vest (27). Whilst no effect was found for the cooling pack, both mixed method cooling trials effectively improved exercise performance (27). The higher cooling capacity in the mixed method cooling compared to individual cooling strategies likely contributes to this finding. Especially mixed techniques with an ‘aggressive' approach and affecting a large body surface seem to contribute to a larger effect on exercise performance. The law of enthalpy of fusion states that ice possesses significantly greater capacity to absorb heat than liquid water (6, 48, 49). Accordingly, more aggressive cooling techniques, typically depending on ice or substances with a temperature below zero, demonstrate a larger effect on changing core body temperature and/or exercise performance. In addition, previous data supports the idea that whole body cooling is more effective than cooling of a part of the body only (27). Indeed, despite the use of a relatively mild stimulus (i.e. 14-24°C), full-body water immersion significantly improved exercise performance (18, 21, 25, 31). The large cooling surface may importantly contribute to the prolonged suppression of increased physiological and thermal loads (22, 50), and thus improve exercise performance. Taken together, a combination of precooling techniques, preferably ‘aggressive’ cooling and interventions that cover a substantial part of the athlete´s body, represent the current 'best practice' model for precooling to improve exercise performance.

Paragraph 20. Also for the percooling strategies, our meta-analysis revealed a significant impact of the type of cooling. Our analyses indicate that wearing an ice-vest during exercise has a significantly larger effect than other percooling techniques (cold water ingestion and cooling packs). Interestingly, the ice vests represent an aggressive cooling strategy that impacts upon a relatively large body surface. This provides further support that also during percooling, strategies with an aggressive nature that aim at a relatively large body surface area are the most effective cooling strategies. An important limitation is that we only included a single study on the impact of an ice vest, which coincidently reported a remarkably large effect size. Nonetheless, the similarities between the type of most effective cooling strategies for pre- and percooling is striking. We strongly support future studies to confirm this finding using well-controlled, within-subjects designs, but also to improve our understanding why and how these aggressive types of cooling are more successful.

Practical recommendations

Paragraph 21.

Our meta-analysis combined the results of 323 subjects in 28 peer-reviewed publications and demonstrated the practical value of cooling strategies to improve exercise performance in the heat. More importantly, we showed that pre- and percooling are equally effective in improving exercise performance in the heat. Therefore, a combination of pre- and percooling may be superior compared to a single strategy alone. Moreover, we revealed that a combination of cooling techniques (for precooling) or ice vests (for percooling) results in the largest effect size on exercise performance, possibly due to the aggressive approach and impact on a relatively large body surface. Based on our novel observations, we recommend future studies to investigate the practical performance and effect size of combining pre- and percooling strategies on exercise performance, preferably using aggressive types of strategies. Such joint efforts can further improve exercise performance in the heat, while it also may contribute to a reduction in heat-related illnesses in athletes.

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Conflict of interest

None of the authors reported a conflict of interest.

Contributorship statement

Bongers, Eijsvogels and Hopman designed the study. Bongers, Thijssen and Eijsvogels performed the literature search and selected the included studies. Veltmeijer and Bongers performed the statistical analysis, and all authors contributed to data interpretation. Bongers and Eijsvogels drafted the manuscript, while Veltmeijer, Thijssen and Hopman critically revised the article. All authors gave their final approval of the version published.

Summary box

- Pre- and percooling are equally effective in improving exercise performance in the heat.

- No correlations were found between measures of performance and ΔTc, ΔTskin and ΔHR for precooling, percooling and the pooled set of cooling studies.
- A combination of cooling techniques (for precooling) or ice vests (for percooling) are preferred to maintain exercise performance in the heat.
- The combination of pre-and percooling techniques could be the most effective strategy to improve exercise performance in the heat.

Reference list

1. Duffield R. Cooling interventions for the protection and recovery of exercise performance from exercise-induced heat stress. *Med Sport Sci*. 2008;**53**:89-103.
2. Wendt D, van Loon LJ, Lichtenbelt WD. Thermoregulation during exercise in the heat: strategies for maintaining health and performance. *Sports medicine (Auckland, NZ*. 2007;**37**:669-82.
3. Maughan R, Shirreffs S. Exercise in the heat: challenges and opportunities. *Journal of sports sciences*. 2004;**22**:917-27.
4. Marino FE. Methods, advantages, and limitations of body cooling for exercise performance. *British journal of sports medicine*. 2002;**36**:89-94.
5. Quod MJ, Martin DT, Laursen PB. Cooling athletes before competition in the heat: comparison of techniques and practical considerations. *Sports medicine (Auckland, NZ*. 2006;**36**:671-82.
6. Siegel R, Laursen PB. Keeping your cool: possible mechanisms for enhanced exercise performance in the heat with internal cooling methods. *Sports medicine (Auckland, NZ*.**42**:89-98.
7. Wegmann M, Faude O, Poppendieck W, et al. Pre-cooling and sports performance: a meta-analytical review. *Sports medicine (Auckland, NZ*. 2012;**42**:545-64.
8. Bolster DR, Trappe SW, Short KR, et al. Effects of precooling on thermoregulation during subsequent exercise. *Medicine and science in sports and exercise*. 1999;**31**:251-7.
9. Kenefick RW, Cheuvront SN, Sawka MN. Thermoregulatory function during the marathon. *Sports medicine (Auckland, NZ*. 2007;**37**:312-5.
10. 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. *British journal of sports medicine*. 2013.
11. Arngrimsson 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.
12. Minett GM, Duffield R, Marino FE, et al. Duration-dependant response of mixed-method pre-cooling for intermittent-sprint exercise in the heat. *European journal of applied physiology*. 2012;**112**:3655-66.
13. Stannard AB, Brandenburg JP, Pitney WA, et al. Effects of wearing a cooling vest during the warm-up on 10-km run performance. *Journal of strength and conditioning research / National Strength & Conditioning Association*.**25**:2018-24.
14. Cohen J. Statistical power analysis for the behavioralsciences. 2 ed. Hillsdale (NJ): Lawrence Erlbaum Associates; 1988. 567 p.
15. Begg CB, Mazumdar M. Operating characteristics of a rank correlation test for publication bias. *Biometrics*. 1994;**50**:1088-101.
16. Egger M, Davey Smith G, Schneider M, et al. Bias in meta-analysis detected by a simple, graphical test. *Bmj*. 1997;**315**:629-34.
17. Sterne JA, Egger M, Smith GD. Systematic reviews in health care: Investigating and dealing with publication and other biases in meta-analysis. *Bmj*. 2001;**323**:101-5.
18. 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.
19. Cotter JD, Sleivert GG, Roberts WS, et al. Effect of pre-cooling, with and without thigh cooling, on strain and endurance exercise performance in the heat. *Comp Biochem Physiol A Mol Integr Physiol*. 2001;**128**:667-77.

20. Duffield R, Dawson B, Bishop D, et al. Effect of wearing an ice cooling jacket on repeat sprint performance in warm/humid conditions. *British journal of sports medicine*. 2003;**37**:164-9.
21. Duffield R, Green R, Castle P, et al. Precooling can prevent the reduction of self-paced exercise intensity in the heat. *Medicine and science in sports and exercise*. 2010;**42**:577-84.
22. Duffield R, Marino FE. Effects of pre-cooling procedures on intermittent-sprint exercise performance in warm conditions. *European journal of applied physiology*. 2007;**100**:727-35.
23. Duffield R, Steinbacher G, Fairchild TJ. The use of mixed-method, part-body pre-cooling procedures for team-sport athletes training in the heat. *Journal of strength and conditioning research / National Strength & Conditioning Association*. 2009;**23**:2524-32.
24. 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. *Canadian journal of applied physiology = Revue canadienne de physiologie appliquee*. 2005;**30**:87-104.
25. Kay D, Taaffe DR, Marino FE. Whole-body pre-cooling and heat storage during self-paced cycling performance in warm humid conditions. *Journal of sports sciences*. 1999;**17**:937-44.
26. Luomala MO, J., Salmi J, Linnamo V, et al. Adding Adding Adding vest during cycling improves performance in warm and humid conditions. *Journal of Thermal Biology*. 2012;**37**:47-55.
27. Minett GM, Duffield R, Marino FE, et al. Volume-dependent response of precooling for intermittent-sprint exercise in the heat. *Medicine and science in sports and exercise*. 2011;**43**:1760-9.
28. 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.
29. Mundel T, King J, Collacott E, et al. Drink temperature influences fluid intake and endurance capacity in men during exercise in a hot, dry environment. *Experimental physiology*. 2006;**91**:925-33.
30. Quod MJ, Martin DT, Laursen PB, et al. Practical precooling: effect on cycling time trial performance in warm conditions. *Journal of sports sciences*. 2008;**26**:1477-87.
31. Siegel R, Mate 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. *Journal of sports sciences*. 2012;**30**:155-65.
32. Stanley J, Leveritt M, Peake JM. Thermoregulatory responses to ice-slush beverage ingestion and exercise in the heat. *European journal of applied physiology*. 2010;**110**:1163-73.
33. Tyler CJ, Sunderland C. Cooling the neck region during exercise in the heat. *Journal of athletic training*.**46**:61-8.
34. Tyler CJ, Sunderland C. Neck cooling and running performance in the heat: single versus repeated application. *Medicine and science in sports and exercise*. 2011;**43**:2388-95.
35. Tyler CJ, Wild P, Sunderland C. Practical neck cooling and time-trial running performance in a hot environment. *European journal of applied physiology*.**110**:1063-74.
36. Uckert S, Joch W. Effects of warm-up and precooling on endurance performance in the heat. *British journal of sports medicine*. 2007;**41**:380-4.
37. Byrne C, Owen C, Cosnefroy A, et al. Self-paced exercise performance in the heat after pre-exercise cold-fluid ingestion. *Journal of athletic training*. 2011;**46**:592-9.
38. 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.

39. 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.
40. Scheadler CM, Saunders NW, Hanson NJ, et al. Palm Cooling Does not Improve Running Performance. *Int J Sports Med*. 2013.
41. Skein M, Duffield R, Cannon J, et al. Self-paced intermittent-sprint performance and pacing strategies following respective pre-cooling and heating. *European journal of applied physiology*. 2012;**112**:253-66.
42. Stevens CJ, Dascombe B, Boyko A, et al. Ice slurry ingestion during cycling improves Olympic distance triathlon performance in the heat. *Journal of sports sciences*. 2013;**31**:1271-9.
43. Burdon CA, Hoon MW, Johnson NA, et al. The Effect of Ice Slushy Ingestion and Mouthwash on Thermoregulation and Endurance Performance in the Heat. *International journal of sport nutrition and exercise metabolism*. 2013.
44. Jones PR, Barton C, Morrissey D, et al. Pre-cooling for endurance exercise performance in the heat: a systematic review. *Bmc Med*. 2012;**10**:166.
45. Reilly T, Drust B, Gregson W. Thermoregulation in elite athletes. *Current opinion in clinical nutrition and metabolic care*. 2006;**9**:666-71.
46. Hasegawa H, Takatori T, Komura T, et al. Combined effects of pre-cooling and water ingestion on thermoregulation and physical capacity during exercise in a hot environment. *Journal of sports sciences*. 2006;**24**:3-9.
47. Tucker R, Rauch L, Harley YX, et al. Impaired exercise performance in the heat is associated with an anticipatory reduction in skeletal muscle recruitment. *Pflugers Arch*. 2004;**448**:422-30.
48. Merrick MA, Jutte LS, Smith ME. Cold Modalities With Different Thermodynamic Properties Produce Different Surface and Intramuscular Temperatures. *Journal of athletic training*. 2003;**38**:28-33.
49. Yeo ZW, Fan PW, Nio AQ, et al. Ice slurry on outdoor running performance in heat. *Int J Sports Med*. 2012;**33**:859-66.
50. Daanen HA, van Es EM, de Graaf JL. Heat strain and gross efficiency during endurance exercise after lower, upper, or whole body precooling in the heat. *Int J Sports Med*. 2006;**27**:379-88.

FIGURE LEGENDS

Figure 1: Overview of selection process of the included studies for this meta-analysis. N indicates the number of studies.

Figure 2: The Funnel plot analysis indicated a possible presence of publication bias due to the asymmetrical shape. The vertical dotted line represents the weighted average effect size of all included studies. The x-axis showed the effect size is shown and the y-axis the standard error of the effect size.

Figure 3: Forest plot summarizing the effects of different cooling techniques on exercise performance for the precooling (A) and the percooling studies (B). The magnitude of the effect size indicates: 0-0.19 = negligible effect, 0.20-0.49 = small effect, 0.50-0.79 = moderate effect and ≥0.80 = large effect (14). The black rectangles represented the weighted effect size and the grey lines are the 95% confidence intervals. The size of the rectangles indicated the weight of the study, which is calculated separately for the precooling and percooling studies.* Studies that used multiple cooling intervention trials were included more than once.

Figure 4. Correlations between change in exercise performance (%) and change in core temperature (ΔTc), skin temperature (ΔTskin) and heart rate (ΔHR) for both precooling (●) and percooling (○). Pearson's correlation coefficient, significance assumed at $p<0.05$. Delta (Δ) = cooling – control.