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Pre-Cooling and Sports Performance

A Meta-Analytical Review

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Abstract

Pre-cooling is used by many athletes for the purpose of reducing body temperature prior to exercise and, consequently, decreasing heat stress and improving performance. Although there are a considerable number of studies showing beneficial effects of pre-cooling, definite conclusions on the effectiveness of pre-cooling on performance cannot yet be drawn. Moreover, detailed analyses of the specific conditions under which pre-cooling may be most promising are, so far, missing. Therefore, we conducted a literature search and located 27 peer-reviewed randomized controlled trials, which addressed the effects of pre-cooling on performance. These studies were analysed with regard to performance effects and several test circumstances (environmental temperature, test protocol, cooling method, aerobic capacity of the subjects).

Eighteen studies were performed in a hot (>26°C) environment and eight in a moderate. The cooling protocols were water application (n = 12), cooling packs (n = 3), cold drinks (n = 2), cooling vest (n = 6) and a cooled room (n = 4). The following different performance tests were used: short-term, high-intensity sprints (n = 2), intermittent sprints (n = 6), time trials (n = 10), open-end tests (n = 7) and graded exercise tests (n = 2). If possible, subjects were grouped into different aerobic capacity levels according to their maximal oxygen consumption ($\dot{V}O_{2max}$): medium 55–65 mL/kg/min (n = 11) and high >65 mL/kg/min (n = 6). For all studies the relative changes of performance due to pre-cooling compared with a control condition, as well as effect sizes (Hedges' g) were calculated. Mean values were weighted according to the number of subjects in each study.

Pre-cooling had a larger effect on performance in hot (+6.6%, g = 0.62) than in moderate temperatures (+1.4%, g = 0.004). The largest performance enhancements were found for endurance tests like open-end tests (+8.6%, g = 0.52), graded exercise tests (+6.0%, g = 0.44) and time trials (+4.2%, g = 0.44). A similar effect was observed for intermittent sprints (+3.3%, g = 0.43), whereas performance changes were smaller during short-term, high-intensity sprints (–0.5%, g = 0.03). The most promising cooling methods were cold drinks (+15.0%, g = 1.68), cooling packs (+5.6%, g = 0.70) and a cooled room (+10.7%, g = 0.49), whereas a cooling vest (+4.8%, g = 0.31) and water application (+1.2%, g = 0.21) showed only small effects. With respect to aerobic capacity, the best results were found in the subjects with the highest $\dot{V}O_{2max}$ (high +7.7%, g = 0.65; medium +3.8%, g = 0.27). There were four studies analysing endurance-trained athletes under time-trial conditions, which, in a practical sense, seem to be most relevant. Those studies found an average effect on performance of 3.7% (g = 0.48).

In summary, pre-cooling can effectively enhance endurance performance, particularly in hot environments, whereas sprint exercise is barely affected. In particular, well trained athletes may benefit in a typical competition setting with practical and relevant effects. With respect to feasibility, cold drinks, cooling packs and cooling vests can be regarded as best-practice methods.

1. Introduction

Performance of the human body is a crucial aspect for different kinds of physical activity.[1] The topic of the present review became relevant for competitive athletes, because sport events often take place in hot environments (e.g. major competitions like the Olympic Games in Atlanta 1996, Athens 2004 and Beijing 2008 or the forthcoming FIFA (Fédération Internationale de Football Association) World Cup in Qatar 2022. High ambient temperatures and humidity lead to an increase in core body temperature and consequently might impair physical performance.[2] For this reason, athletes will consider the use of cooling methods when competing in hot environments in order to counteract a potential reduction in performance.

In recent years, the discussion about the use of cooling methods and devices in competitive sport has gained interest not only in hot environments, but in other areas also.[3-5] One application that has frequently been investigated to enhance performance is cooling prior to exercise (pre-cooling).

The proposed physiological mechanism of pre-cooling is to reduce heat stress on the thermoregulatory system and to consequently delay the onset of thermally induced fatigue. Pre-cooling can positively influence the cardiovascular system (blood distribution to the working muscles and redistribution from the periphery to the body core), metabolism (preserving optimal temperature for enzyme activity), as well as the central and the peripheral nervous system (suppressing inhibitory neuronal signals from the central governor).[6,7] However, the exact physiological mechanisms underlying possible performance improvements and their interaction are not completely understood yet.[6]

Especially during the last 20 years, a large number of studies have been published focusing on pre-cooling but on the basis of currently existing studies it is still difficult to arrive at practical guidelines for the application of pre-cooling. This is due to the inhomogeneous methodology used in the respective studies. For instance, different cooling protocols were combined with a diversity of exercise tests at various ambient temperatures in subjects of heterogeneous fitness levels. Thus, to analyse the effect of pre-cooling with respect to these various conditions, it is important to evaluate and classify the existing studies.

The present meta-analytical review was conducted to give an overview about the current scientific literature in the field of pre-cooling. Based on the existing studies, the effectiveness of pre-cooling for exercise performance was evaluated with regard to effects on performance under various circumstances (ambient temperature, test protocol, cooling method, aerobic capacity of the subjects). Moreover, effective and feasible cooling methods for practical applications were identified and efficient, evidence-based, pre-cooling strategies for training and competition were developed.

2. Methods

A literature search was undertaken, using 11 different keywords ('pre-cooling/precooling', 'cooling', 'intervention', 'performance', 'exercise', 'effects', 'body temperature', 'water immersion', 'cooling vest', 'ice slurry', 'thermoregulation'), which were combined by Boolean logic (AND). For the research, the following databases were used: PubMed, ISI Web of Science, the Allied and Complementary Medicine Database (AMED), the Cochrane Database of Systematic Reviews and the Excerpta Medica Database (EMBASE). This was complemented with citation tracking of key primary and review articles.

2.1 Selection Criteria

The obtained articles were evaluated with respect to their suitability and significance for the desired context. This was done based on various criteria. A study was only included if it fulfilled the following requirements:

1. The cooling intervention had to take place before exercise.
2. The existence of a control condition without cooling, i.e. with the subjects acting as their own controls (randomized crossover design).
3. Measurement of exercise performance, as only under such circumstances it is possible to quantify the effect of pre-cooling on performance. For instance, studies that only evaluated the effects of pre-cooling on physiological markers (heart rate, blood lactate concentrations, oxygen consumption, etc.) were excluded.
4. The number of studies with elite athletes as subjects was limited and, thus, studies with trained athletes (not necessarily elite athletes) were included (maximal oxygen consumption [$\dot{V}O_{2max}$] $\geq$55 mL/kg/min).[8] Studies with untrained subjects ($\dot{V}O_{2max}$ <55 mL/kg/min) were not considered. Also, as only one study analysed women,[9] this criterion was applied to male athletes. In case $\dot{V}O_{2max}$ was not mentioned, the study was only included if the authors clearly stated that the athletes were trained.
5. The study must have been published in an internationally peer-reviewed scientific journal.

Figure 1 shows the flow chart of the selection process. Finally, 27 remaining studies were analysed.

2.2 Classification of the Studies

For further analyses, studies were classified into different groups with respect to the following criteria:

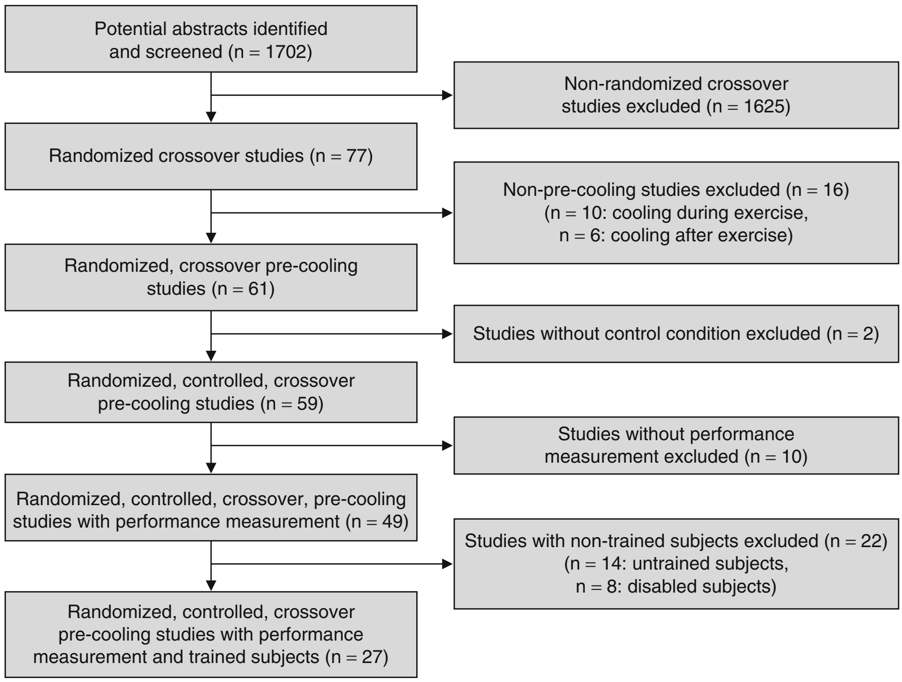

Fig. 1. Summary of the study selection process.

1. Ambient temperatures of the studies were divided into two groups (hot [>26°C] and moderate [18–26°C]) according to Parsons.[10]
2. Another criterion for classification was the cooling protocol used. Five different types of cooling protocols were identified: cold drinks, cooling packs, a cooled room, cooling vests and water application.
3. In the studies, five types of exercise protocol were used: sprint (short-term, high-intensity exercise up to a duration of about 70 seconds, as energy supply during such exercise is mainly covered by anaerobic pathways[11]), intermittent sprints (repeated sprints interrupted by breaks or low-intensity exercise), time trials (exercise against the clock with fixed total distance or duration), open-end tests (exercise until exhaustion at a fixed intensity), and graded exercise tests (exercise until exhaustion with stepwise increasing intensity). All endurance exercise tasks lasted for at least 6 minutes and, thus, aerobic energy delivery was dominant.
4. The male subjects were further classified according to their aerobic capacity level ($\dot{V}O_{2max}$). Two groups were formed: medium (55–65 mL/kg/min) and high (>65 mL/kg/min).

2.3 Assessment of Effect Sizes and Statistical Analyses

For each study, standardized mean differences (Hedges' g) and 95% confidence intervals were computed separately. This was done based on the difference in performance between the intervention and the control condition and the pooled standard deviation. When studies reported only standard errors, standard deviations were calculated by multiplying standard errors by the square root of the sample size. To correct for small sample size bias, the bias-corrected Hedges' g was used. Negative effects (performance impairments due to pre-cooling) were denoted with a minus sign. Overall outcome for the analysed conditions was assessed by calculating weighted g averages. Data for all single studies, as well as weighted average values, were presented in forest plots. The magnitude of g was classified according to 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.[12] To evaluate a possible publication bias a qualitative funnel plot analysis was done. Statistical analysis was performed using the software package Statistica 8.0.

3. Results

3.1 Search Results

In total, 1702 articles were found out of which 77 articles were peer-reviewed crossover studies. These articles were evaluated according to the specified inclusion criteria (see figure 1). Twenty-seven studies with a total number of 269 subjects were identified that met all inclusion criteria. An overview of these studies is given in table I.

Eighteen studies were performed in a hot environment and eight in a moderate (for one study no information about the ambient temperature was available). The used cooling protocols were water application (n = 12), cooling packs (n = 3), cold drinks (n = 2), cooling vests (n = 6) and a cooled room (n = 4). With respect to the type of exercise, the following groups were formed: sprint (n = 2), intermittent sprint (n = 6), time trials (n = 10), open-end tests (n = 7) and graded exercise tests (n = 2). Eleven studies included subjects with medium and six with high aerobic capacity levels (for n = 10 studies no data on $\dot{V}O_{2max}$ were available). Almost all studies used only male subjects, except for one (Arngrimsson et al.[9]) having both male and female athletes. For this study, the $\dot{V}O_{2max}$ group assignment was based only on male values.

The weighted average increase of performance in all studies was 4.9%, the weighted average effect size was 0.41. Figure 2 shows a funnel plot of all 27 studies. The plot shows an almost symmetrical shape with effect sizes approaching the average value with an increasing number of participants. This can be regarded as an indication that no publication bias is present.

3.2 Effect of Ambient Temperature

Figure 3 shows the relation between ambient temperature and the effect of pre-cooling. In the upper part of the figure, the eight studies under moderate ambient temperature are summarized; the lower part shows the 18 studies performed in a hot ambient temperature. A tendency to higher pre-cooling effects with increasing ambient temperature can be observed. Among the studies under moderate temperature, the pronounced negative effect in the study of Bergh and Ekblom[13] is remarkable. For the studies with a high ambient temperature, only the study of Mitchell et al.[29] showed a negative effect of pre-cooling.

3.3 Effect of Exercise Duration and Type of Exercise

In figure 4 the influence of exercise duration on the pre-cooling effect is presented. The studies using sprint and intermittent sprint protocols are shown in the upper part of the figure, the studies with endurance protocols (time trials, open-end tests and graded exercise tests) are summarized in the lower part of the figure. Average effects on performance were larger in endurance events compared with sprint performance. For endurance exercise in particular, a tendency towards larger effects for increasing exercise duration can be seen. However, it seems that there is a threshold for exercise duration (approximately 60 minutes) beyond which the pre-cooling effects are reduced again.

3.4 Effect of Cooling Method

Figure 5 shows the cooling method plotted against the effect size of performance enhancement. For each cooling method, the studies are ordered by cooling duration. On average, the best results were found for cold drinks (+15.0%, g = 1.68). However, for this method only two studies were analysed. Medium average effect sizes were observed for cooling packs (+5.6%, g = 0.70), while the effects for cooled rooms (+10.7%, g = 0.49), cooling vests (+4.8%, g = 0.31) and water application (+1.2%, g = 0.21) were only small.

3.5 Effect of Fitness Level

The influence of fitness level ($\dot{V}O_{2max}$) on the effects of pre-cooling on performance is depicted in figure 6. It is observed that pre-cooling can also have a positive effect in highly endurance-trained

Table I. Overview of the analysed studies

Study	No. of subjects and training status ($\dot{V}O_{2max}$ in mL/kg/min)[a]	Performance measurement	Temperature (relative humidity)	Cooling method (duration)	Performance effect Hedges' g (relative change)
Arngrimsson et al.[9]	17 Well trained medium- and long-distance runners (female: 58 ± 3.2, male: 66.7 ± 5.9	5 km time trial on a treadmill	32°C, (50%)	Cooling vest during warm-up (38 min)	0.1 (+1.1%)
Bergh and Ekblom[13]	8 Well trained subjects (59.4 ± 5.5)	Open-end test on a cycle ergometer for combined arm and leg exercise at 110% $\dot{V}O_{2max}$	20–22°C (NA)	Swimming [13–15°C water temperature] at 40–60% $\dot{V}O_{2max}$ (15–25 min)	–2.0 (–36.0%)
Bogerd et al.[14]	8 NA (57.1 ± 4.7)	Open-end test on a cycle ergometer at 65% $\dot{V}O_{2max}$	29°C (90%)	Cooling vest (45 min)	1.1 (+17%)
Booth et al.[15]	8 Competitive runners (63.1 ± 0.1)	30 min time trial on a treadmill	32°C (60%)	Cold water application [whole body] 23–24°C (60 min)	0.6 (+4.2%)
Cheung and Robinson[16]	10 Well trained triathletes (59 ± 11.4)	30 min intermittent sprint on a cycle ergometer	22°C (40%)	Cooling vest 75 min or until rectal temperature was reduced by 0.5°C	–0.1 (–1.1%)
Drust et al.[17]	6 University soccer players (58.9 ± 3.5)	Soccer-specific exercise on a treadmill for 90 min	21°C (72%)	Whole-body showering [28–24°C] (60 min)	–0.2 (–1.1%)
Duffield et al.[18]	7 First division hockey players (NA)	80 min intermittent sprint on a cycle ergometer	30°C (60%)	Cooling vest (25 min)	0.2 (+2.4%)
Duffield et al.[19]	7 NCAA division 1 lacrosse players (NA)	4 × 5 min bouts of intermittent-sprint exercise, separated by 2 min of passive recovery	32°C (44%)	20 min cooling packs	1.4 (+7.7%)
Duffield et al.[20]	8 Trained cyclists [lactate threshold 221 Watts, weight 76 kg] (NA)	40 min time trial on a cycle ergometer	33°C (50%)	Lower body cooling in water [14°C] at 22°C room temperature (20 min)	1.0 (+7.2%)
Duffield and Marino[21]	9 Well trained club-level rugby players (NA)	2 × 30 min repeated 15 m sprints	32°C (30%)	Cooling vest (15 min [+10 min half-time cooling])	0.3 (+0.4%)
Gonzalez-Alonso et al.[2]	7 Well trained cyclists (65.9 ± 3.9)	Open-end test on a cycle ergometer at 60% $\dot{V}O_{2max}$	40°C (19%)	Cold water application at 17°C (30 min)	2.1 (+37.0%)
Hessemer et al.[5]	8 Well trained rowers (65.8 [57.3–78.0])	60 min time trial on a cycle ergometer	18°C (NA)	Cold room, temperature range 0–18°C (90 min)	2.4 (+6.8%)
Hornery et al.[22]	14 Cyclists (57.1 ± 11.1)	10 min time trial on a cycle ergometer	21°C (33%)	Cooling vest (10 min)	0.2 (+4.0%)

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Table I. Contd

Study	No. of subjects and training status ($\dot{V}O_{2max}$ in mL/kg/min)[a]	Performance measurement	Temperature (relative humidity)	Cooling method (duration)	Performance effect Hedges' g (relative change)
Ihsan et al.[23]	7 Endurance trained, regularly competing in cycling or triathlon events (NA)	40 km time trial on a cycle ergometer	30°C (74%)	Ingestion of crushed ice [6.8 g/kg] (30 min)	0.4 (+6.5%)
Kay et al.[24]	7 Well trained cyclists (64.5 ± 3.3)	30 min time trial on a cycle trainer	31°C (60%)	Cold water application [whole body], until skin temperature was reduced by 5–6°C (60 min)	0.4 (+6.0%)
Lee et al.[25]	8 Trained athletes (57.8 ± 5.6)	Open-end test on a cycle ergometer at 65% $\dot{V}O_{2max}$	35°C (60%)	3 × 300 mL cold drinks [4°C] (30 min)	2.8 (+22.0%)
Lee and Haymes[26]	14 Trained runners (56.5 ± 4.9)	Open-end test on a treadmill at 82% $\dot{V}O_{2max}$	24°C (51–52%)	Cold room, 5°C (33 min)	0.4 (+17.0%)
Marsh and Sleivert[27]	13 Elite cyclists (66.1 ± 7.0)	70 sec sprint on a cycle ergometer	29°C (80%)	Cold water application [only upper body 18–14°C] (30 min)	0.4 (+3.8%)
Minett et al.[28]	10 Well trained team sport athletes (NA)	2 × 35 min free-paced, intermittent-sprint exercise	33°C (33%)	Whole-body cooling with cooling packs (25 min)	0.9 (+10.0%)
Mitchell et al.[29]	11 Endurance-trained competitive runners (54.8 ± 4.2)	Open-end test on a treadmill at $\dot{V}O_{2max}$	38°C (40%)	Ambient temperature 22°C, fan cooling with water spraying (20 min)	–0.5 (–7.5%)
Myler et al.[30]	12 Elite rowers (NA)	6 min time-trial rowing ergometer	30°C (30%)	Cooling packs (5 min)	0.1 (+1.1%)
Olschewski and Brück[3]	9 Trained runners (60.0 ± 9.3)	Open-end test on a cycle ergometer at 80% $\dot{V}O_{2max}$	18°C (50%)	Cold room, temperature range 0–18°C (90 min)	0.4 (+12.4%)
Quod et al.[31]	6 Trained cyclists (71.4 ± 3.2)	Fixed intensity on a cycle ergometer: 20 min at 75% $\dot{V}O_{2max}$, then self-paced intensity until same work as during first part was reached	34°C (41%)	Cold water application [whole body at 29–24°C] (30 min) + cooling vest (40 min)	1.1 (+3.8)
Schmidt and Brück[4]	12 Well trained rowers (61.5 [42–81])	Stage test until exhaustion on a cycle ergometer	18°C (NA)	Cold room, temperature range 0–18°C (90 min)	0.4 (+3.4%)
Schniepp et al.[32]	10 Highly trained cyclists (NA)	30 sec sprint on a cycle ergometer	Moderate (NA)	Cold water application [whole body, 12°C] (15 min)	–0.5 (–6.1%)
Ückert and Joch[33]	20 High-level athletes [soccer, athletics] (NA)	Stage test until exhaustion on a treadmill	30–32°C (50%)	Cooling vest [0–5°C] (20 min)	0.5 (+7.3%)
Yeargin[34]	15 Highly endurance-trained runners (NA)	3.2 km time trial (running)	Approx. 27°C (NA)	Cold water application at 14°C (12 min)	0.4 (+6.0%)

a Data for $\dot{V}O_{2max}$ in mL/kg/min are presented in mean ± standard deviations or mean [range] where stated.

Approx. = approximately; **NA** = not applicable; **NCAA** = National Collegiate Athletic Association; $\dot{V}O_{2max}$ = maximal oxygen consumption.

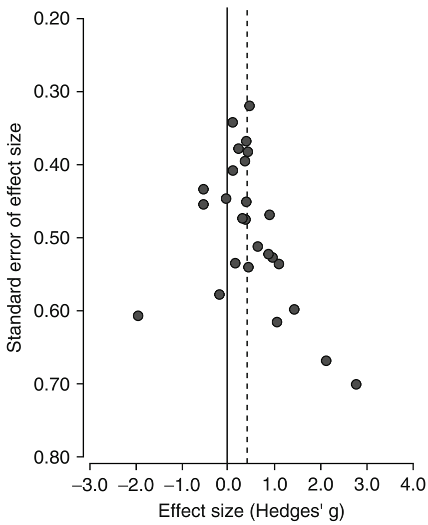

Fig. 2. Funnel plot analysis indicating no publication bias. The vertical dotted line represents the average effect size of all included studies.

athletes. For the subjects with a $\dot{V}O_{2max}$ >65 mL/kg/min an average performance enhancement of +7.7% (g = 0.65) was found. The subjects with medium $\dot{V}O_{2max}$ (55–65 mL/kg/min) showed an average performance enhancement of +3.8% (g = 0.27).

Four studies[5,9,24,35] investigated highly endurance-trained athletes in time trials, which are most relevant from a practical point of view (see corresponding references in figures 4 and 6, as well as in table I). For these studies, an average increase in performance of 3.7% (g = 0.48) was found.

4. Discussion

Evaluation of the existing pre-cooling studies revealed an average performance enhancement of 4.9% (g = 0.41). The effectiveness of pre-cooling depended on various conditions of the study protocol. The largest effects can be expected in hot environmental temperatures and for endurance exercise. It could also be further shown that highly endurance-trained athletes can benefit from a pre-cooling effect relevant to the conditions.

4.1 Physical Performance and Fatigue in the Heat

The effects of heat on physical performance basically depends on environmental temperature, relative humidity, the athlete's ability to regulate his core temperature and on the intensity and duration of exercise.[36] For instance, if extensive sweating leads to a fluid deficit of 1.5–2%, this usually causes a detrimental effect on performance.[37] In addition to dehydration, sweating involves a loss of electrolytes, which might further impair muscle performance, as well as muscle coordination.

While short-term maximum contraction of the skeletal muscles is not affected by heat,[38] continuous muscle performance is typically impaired by hyperthermia. This was shown for intermittent sprint exercise,[39] as well as medium- and long-term endurance performance.[1,2,40] The physiological mechanisms leading to heat-provoked fatigue are manifold. Nybo[1] postulated a combination of central and peripheral mechanisms, which, depending on the specific situation, play a greater or lesser part in fatigue.

Central fatigue is assumed to be initiated by superordinate functional centres of the central nervous system.[41] In the heat, the contribution of the central nervous system to fatigue might be larger than at moderate temperatures.[37,42] Further evidence is provided by a study, which demonstrated that volitional muscle contraction after exercise in the heat (40°C) was reduced compared with moderate ambient temperatures (18°C).[40] In the same study, it was found that muscle contraction could be sustained during external electrical nerve stimulation, suggesting a central cause of fatigue during isometric muscle contractions. Several studies showed that volitional muscle contraction could only be sustained up to a certain core body temperature.[43,44] Comparing the temperature increase of body core and brain in goats, Caputa et al.[45] observed that high hypothalamic temperature is probably the main factor impairing motor activity.

The thermoreceptors of the hypothalamus detect temperature increases and have a regulatory function by sending inhibitory signals to motor

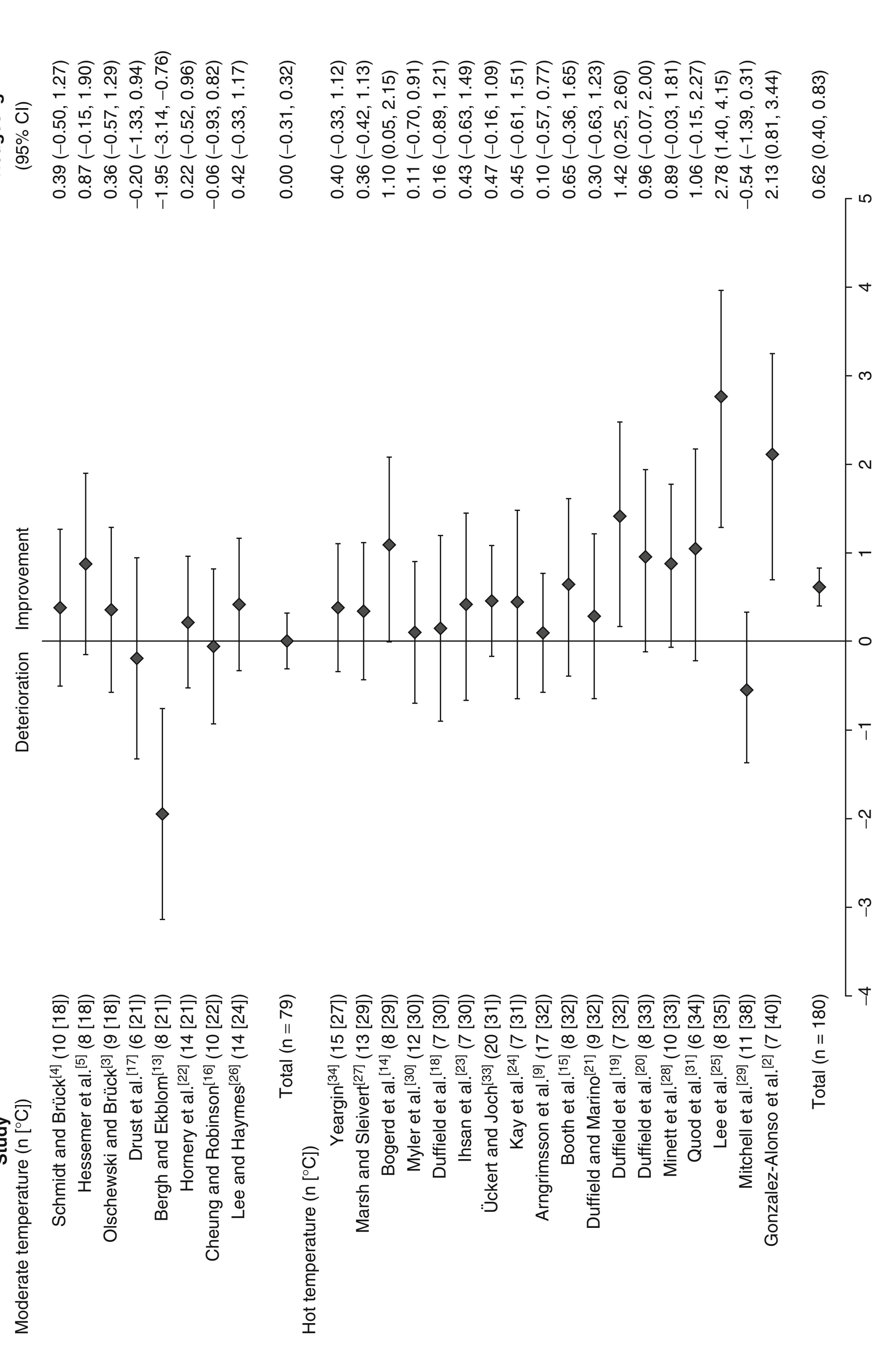

Fig. 3. Effects of pre-cooling on performance related to ambient temperature. The magnitude of the effect size indicates: 0–0.19 = negligible effect, 0.20–0.49 = small effect, 0.50–0.79 = moderate effect, ≥0.80 = large effect. **CI** = confidence interval; **n** = number of subjects.

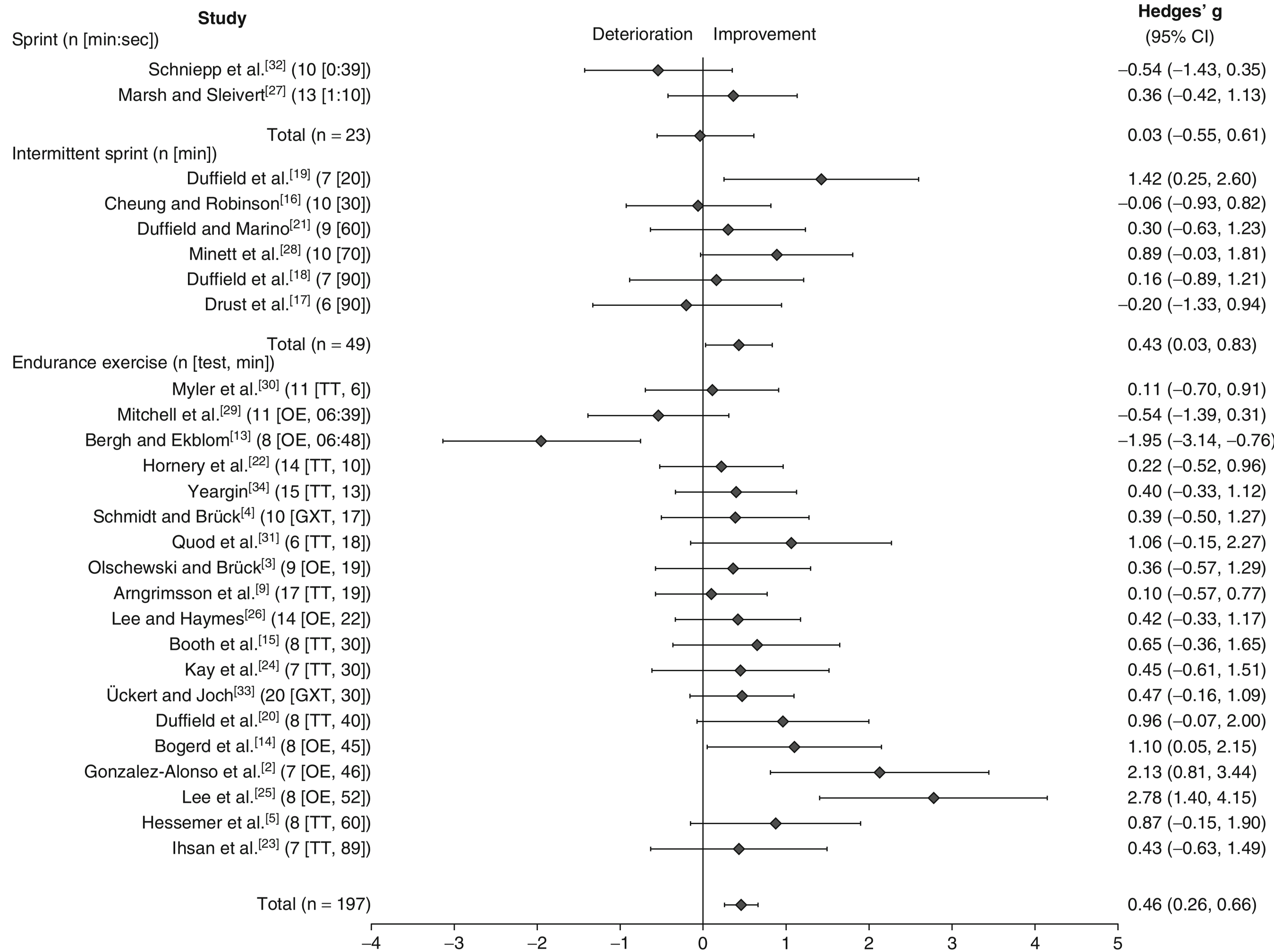

Fig. 4. Effects of pre-cooling on performance related to exercise type and duration. The magnitude of the effect size indicates: 0–0.19 = negligible effect, 0.20–0.49 = small effect, 0.50–0.79 = moderate effect, ≥0.80 = large effect. **CI** = confidence interval; **GXT** = graded exercise test; **n** = number of subjects; **OE** = open-end test; **TT** = time trials.

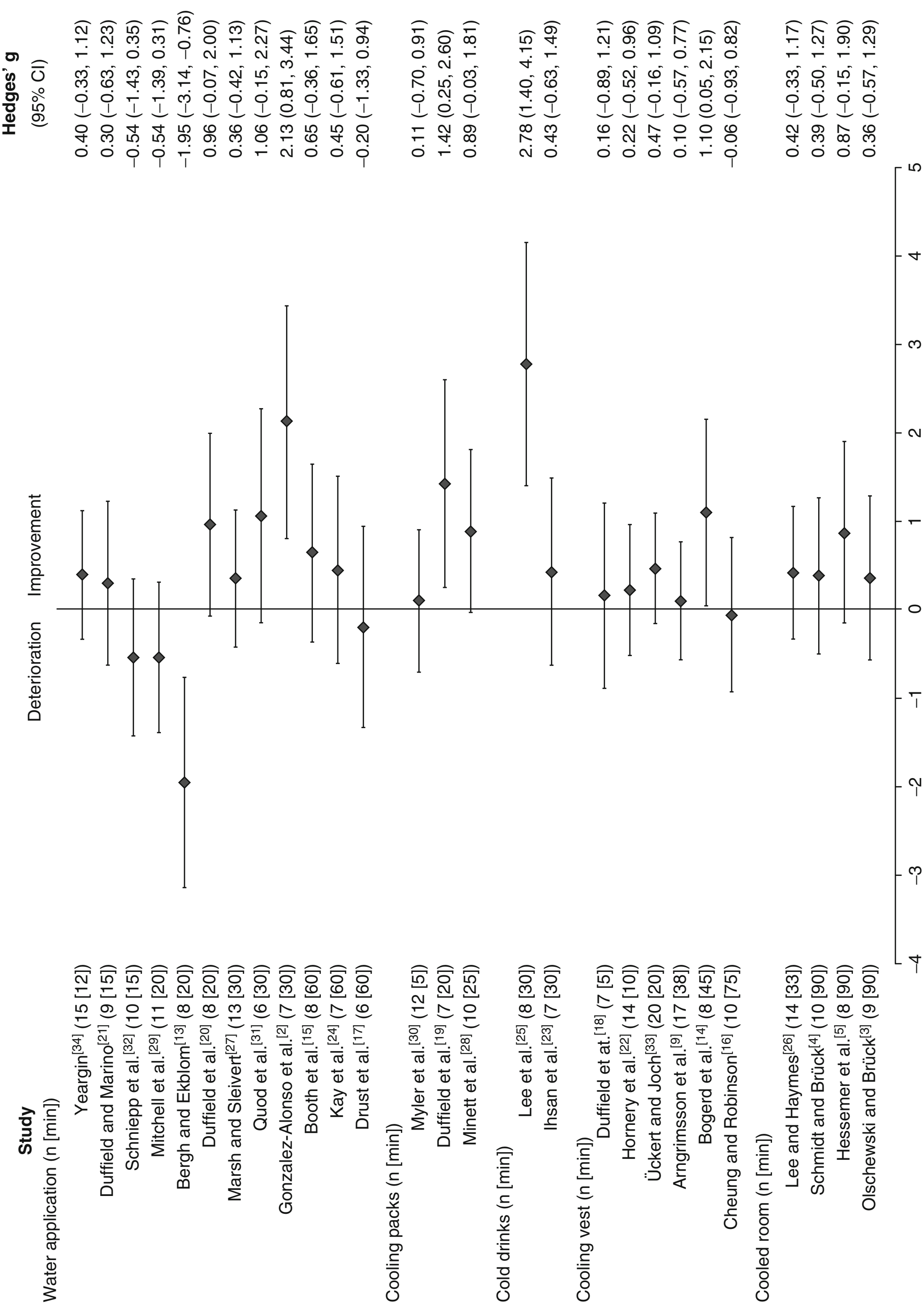

Fig. 5. Effects of pre-cooling on performance related to cooling method and duration. The magnitude of the effect size indicates: 0–0.19 = negligible effect, 0.20–0.49 = small effect, 0.50–0.79 = moderate effect, ≥0.80 = large effect. **CI** = confidence interval; **n** = number of subjects.

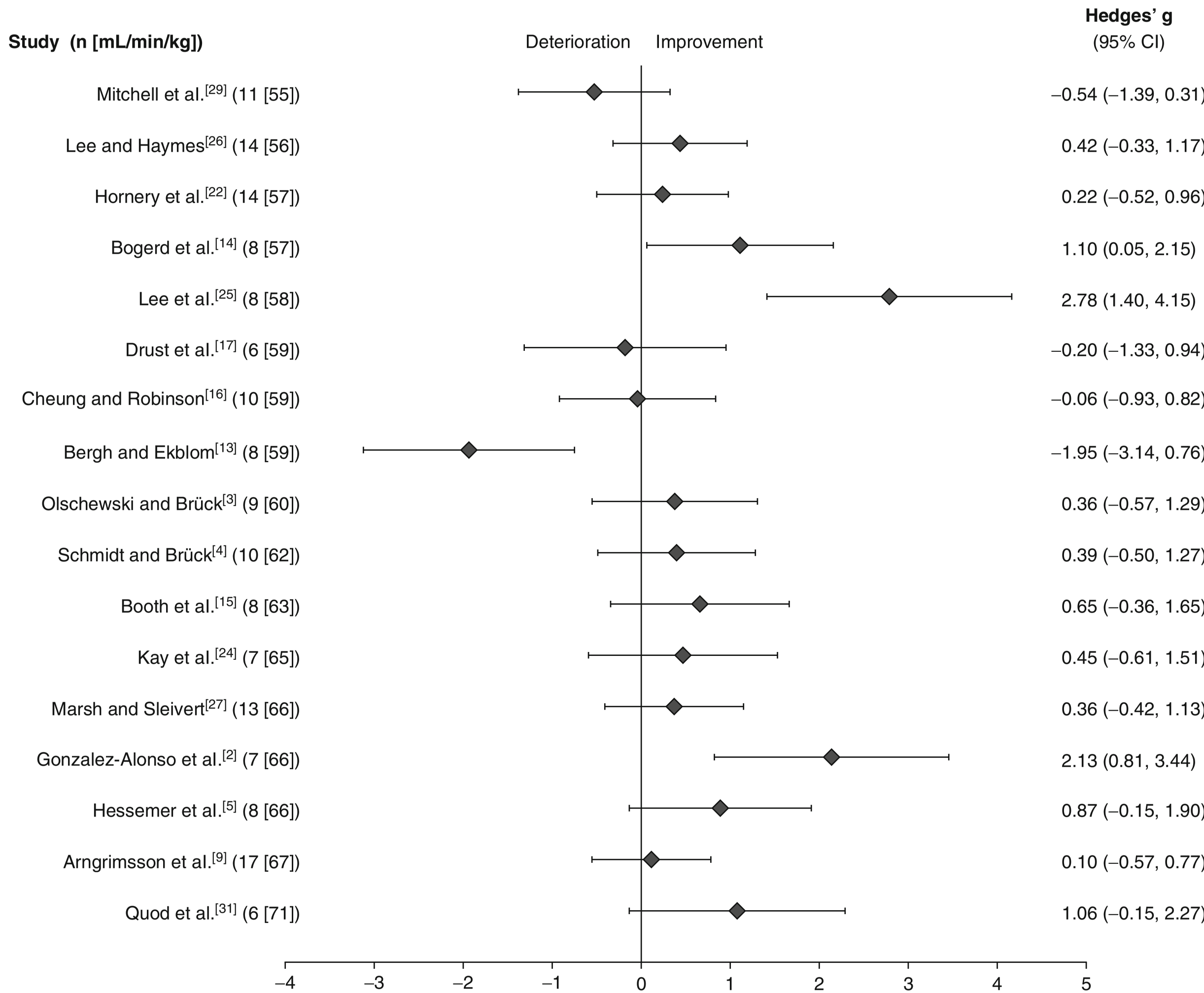

Fig. 6. Effects of pre-cooling on performance related to $\dot{V}O_{2max}$. The study by Arngrimsson et al.[9] was the only study including women. For comparability reasons, only the $\dot{V}O_{2max}$ values of the male subjects were considered. The magnitude of the effect size indicates: 0–0.19 = negligible effect, 0.20–0.49 = small effect, 0.50–0.79 = moderate effect, ≥0.80 = large effect. **CI** = confidence interval; **n** = number of subjects; $\mathbf{\dot{V}O_{2max}}$ = maximal oxygen consumption.

control centres.[1] Likewise, inhibition caused by chemo- and metaboreceptors in the muscles seems to be important in central fatigue. Heat causes hyperventilation and, thus, also hypocapnia; consequently, cerebral blood flow can be reduced. A lower oxygen partial pressure causes central fatigue, before cerebral metabolism and muscular motor function are impaired.

Temperature changes can also influence cardiovascular function. Due to the redistribution of blood from the core to the periphery (increased skin perfusion due to vasodilatation of the blood vessels of the skin to improve heat dissipation), an adequate (higher) cardiac output is maintained by an increased heart rate. Stroke volume is decreased with increasing core body temperature, because the reduced central blood volume leads to a lower filling pressure, and diastolic filling time is reduced due to a higher heart rate.[46] In this context, the arteriovenous anastomoses of the skin play an important role, as they are opened with increasing body temperature and create a short cut between arteries and veins. Blood flowing through these cross connections does not flow through capillaries and can thus not be used for exchange of nutrients and oxygen. With respect to metabolism, lactate and glycogen depletion do not appear to be a limiting factor for submaximal exercise in the heat.[2]

It can be concluded that, depending on the type of exercise, different mechanisms play different roles in the development of heat-induced fatigue. While endurance exercise is impaired by heat, muscle force in short-term sprint performance remains unaffected. It is supposed that short-term, high-intensive exercise is mainly limited by cardiocirculatory factors. In long-term, submaximal exercise performance, limitation in the heat is primarily caused by central fatigue.[1]

4.2 Mechanisms of Pre-Cooling

The mechanisms underlying the performance enhancement of pre-cooling are not fully understood yet.[7] However, the existing pre-cooling studies often undertake a lot of measurement effort.

Lee and Haymes[26] discuss the causes of performance enhancement in an open-end test until exhaustion, and presume a reduction of stored heat in the body after pre-cooling; thereby, the body can absorb more heat during exercise. Increased heat storage capacity after pre-cooling is also suggested by Booth et al.[15] and Kay et al.[24] Thus, thermal stress is reduced, which is indicated during exercise by a reduced body temperature.

A lower heart rate can be another sign of reduced thermal stress.[24,35] In 23 of 27 studies, heart rate was reduced or unchanged after pre-cooling, although performance was partly higher. Olschewski and Brück[3] talk about possible causes of the reduced heart rate after pre-cooling. They suggest influences of the Q10 rule (the velocity of biological and chemical processes increase with temperature) and of baroreflexes caused by changes in skin temperature. Moreover, Schmidt and Brück[4] suggest a higher venous tension leading to increased venous return, as well as improved oxygen utilization in the blood. The latter may be influenced by a delayed opening of the arteriovenous anastomoses.

Reduced thermal stress is also reflected in a lower sweat rate.[5] Lee and Haymes,[26] as well as Duffield et al.,[20] explain a beneficial effect on performance by a reduced sweat rate and, hence, a slower plasma volume reduction. All this would lead to a reduced danger of dehydration. With regards to endurance exercise of longer duration, central mechanisms of fatigue seem to gain importance.[20,47] It has been suggested that pre-cooling changes the sensory feedback of the thermoregulatory system, attenuating overheat protection mechanisms of the central nervous system.[21,48] Thereby, performance can be maintained for a longer time. However, due to the altered sensory feedback and the reduced protection mechanisms, heat-induced damage might occur.[49]

Many studies have reported an increase in central blood volume and, thus, improved perfusion of the working muscles caused by peripheral vasoconstriction due to reduced skin temperature.[14,15,18,21,22,27,30] An improved central blood supply can be indicated by a reduced heart rate[29] and a larger stroke volume[2,9] during exercise after pre-cooling. An increased stroke volume is possibly caused by increased venous return due to less pooling of blood in the skin, as well as a higher myocardial contractility due to reduced core body temperature and sympathetic activation.[2]

In addition to the physiological effects of pre-cooling, psychological effects have to be considered as well. In the studies analysed, this was usually reflected by scales of thermal sensation and/or the ratings of perceived exertion. In this context, it seems noteworthy that psychological effects had a stronger influence on performance in a warm environment.[15,20,22,25,27,34,48] However, these findings were not consistently reported. No changes in psychological effort were observed in several other studies.[2,9,13,17,21,24,26,31] Nevertheless, it has to be considered that performance was, on average, improved after pre-cooling and, thus, the sensation of effort might have been unchanged due to the increased exercise intensity.

4.3 Effects of Pre-Cooling with Regard to Exercise Duration and Ambient Temperature

It has been suggested that pre-cooling can only have a relevant impact on performance if thermal stress is large enough, i.e. for longer exercise durations and/or high ambient temperature.[21] Accordingly, a tendency towards increasing effect size for longer exercise durations has been observed in the present analysis. However, for durations above 60 minutes, the effect of pre-cooling seems to decrease, probably due to a limited duration of the cooling effect.[5,17,26]

Our results also confirm the assumption by Duffield and Marino[21] that only large thermal stress pre-cooling can be expected to have a relevant effect. The two studies with the highest effect sizes are among the three studies with the highest ambient temperatures.[2,25] A general tendency to a higher effect with increasing ambient temperature is observed. This observation is further confirmed by the effect sizes for warm (0.62) and moderate (0.004) conditions. Only in one study was a negative performance effect of pre-cooling at high ambient temperature found.[29] This may be due to an uncomfortable cooling protocol used (the subjects were exposed to a fan for 20 minutes and water was sprayed on them). Also, the core body temperatures reached at the end of exercise in this study (approximately 39°C) suggest that no state of excessive hyperthermia was reached.

4.4 Type of Exercise and Pre-Cooling

The effect of pre-cooling also depends on the type of exercise. In the past, the focus of many pre-cooling investigations was on endurance performance in a hot environment.[6,35] The present results show that for endurance exercise, a larger pre-cooling effect was found compared with sprint or intermittent sprint. With regard to the type of exercise, the highest relative performance enhancement was found in open-end tests. However, average effect sizes were similar for the three types of endurance exercise (graded exercise tests, open-end tests and time trials). The reason for the comparatively larger percentage effects in open-end exercise can be seen in the larger baseline variability of time to exhaustion during this kind of exercise compared with average power output during time-trial protocols.[50]

While attenuation of the protective mechanisms of the central nervous system may be relevant for all endurance protocols, in the time-trial condition also, anticipation mechanisms can influence performance due to the self-chosen intensity (pacing).[51] In this sense, pacing represents an anticipatory response to afferent information about stored body heat.[47] Accordingly, in several studies, performance after pre-cooling in comparison to the control condition increased only at a later stage of exercise and thus at a stage when the measurable pre-cooling effects (e.g. core body temperature reduction) were already alleviated.[5,9,15,20,34]

Out of the two sprint studies included, one showed a small-positive[27] and the other a medium-negative effect.[32] In the first case, the authors assume a redistribution of blood from the periphery to the working muscles caused by vasoconstriction to be the main mechanism of pre-cooling. However, in a later publication, one of the authors suggests that placebo effects could have had an influence.[52]

The study by Schniepp and colleagues[32] showed that pre-cooling can also have a detrimental effect on sprint performance. Compared to Marsh and Sleivert,[27] the test protocol differed in several ways. In the study by Marsh and Sleivert,[27] exercise was performed in warm environment. Under the assumption that central blood volume increase is a decisive mechanism of pre-cooling, it can be suspected that, compared with the control condition, pre-cooling in a warm environment leads to a stronger reduction of skin perfusion than in a moderate environment. Moreover, Marsh and Sleivert[27] used a 10-minute warm-up programme, while in the study of Schniepp and colleagues[32] exercise was started immediately after cooling. Another considerable difference was the cooling protocol. In contrast to Marsh and Sleivert, Schniepp et al. cooled the working muscles directly, which can have a negative effect on performance.[52,53]

In the studies on intermittent sprint exercise, pre-cooling had a small average effect on performance. Two studies showed a small reduction in performance,[16,17] whereas four studies demonstrated a small-[18,21,48] or large-positive[28] effect. It should be noted that the studies with a negative effect were performed at moderate temperatures (21–22°C), whereas the studies with a positive effect were executed in warm conditions (30–34°C). Drust and colleagues[17] argue that for intermittent sprint exercise, thermal stress is higher than for continuous exercise, and for this reason they assume that pre-cooling is more likely to have a positive effect. However, a general statement is difficult, as on one hand, for continuous exercise, the described effects also depend on the intensity, and on the other, an adequate database regarding this topic is nonexistent.

A possible reason for the small effects of pre-cooling on intermittent sprint performance could be exercise duration. By relating the pre-cooling effects to exercise duration, it became evident that after 60 minutes of exercise the effects of pre-cooling were reduced. It has been speculated that pre-cooling is only effective for a duration of 30–40 minutes.[5,17,26] Therefore, for team sports (e.g. soccer), half-time cooling could be of interest. However, Duffield and colleagues[18] cooled their subjects during exercise breaks and, nevertheless, did not achieve any large positive effects on performance. In this context, the opposite approaches also exist, which showed that intermittent sprint performance could be significantly improved by rewarm up instead of pre-cooling during exercise breaks.[54] Further research is necessary to arrive at valid conclusions under which circumstances pre-cooling can be effective in intermittent high-intensity sports.

Interestingly, there were also differences when analysing the mode of exercise during endurance tasks (run vs bike) with considerably greater effect sizes for cycling (n = 14 studies, g = 0.68 [95% CI 0.42, 0.94]) compared with running exercise (n = 10 studies, g = 0.37 [95% CI 0.11, 0.62]). In particular, differences were more pronounced in a hot environment (bike: g = 1.16, run: g = 0.40). The reasons for this finding must remain speculative. Possibly, the missing head wind during cycling in the laboratory compared with the real-world situation may partly explain that result. However, different effects of pre-cooling due to exercise mode remain an interesting topic for future research.

4.5 Does Aerobic Capacity have an Effect on Pre-Cooling Efficacy?

In the context of practical recommendations, the influence of the fitness level on pre-cooling effects is of special interest. It can be expected that elite athletes tap their physiological potential to a higher degree than less trained athletes.[55] Moreover, it has been shown that elite athletes have a better adapted thermoregulatory system compared with untrained subjects.[56,57] For these reasons, it might be speculated that in elite sport pre-cooling has a lower effect on performance than in recreational athletes. However, our analysis showed that for athletes with a high $\dot{V}O_{2max}$ (65–75 mL/min/kg) the weighted average effect size and relative performance change was highest. Moreover, for these athletes, all studies showed a positive effect. Even though it has to be considered that in these studies five of six used an endurance protocol (for which a higher effect can be expected), it must be pointed out that athletes with a high $\dot{V}O_{2max}$ can still improve their endurance performance during time trials, as this is particularly the type of exercise which is most relevant in a real-world competitive setting.

In the context of methods with the potential to enhance endurance performance, the minimum improvement making a certain strategy worthwhile is an important item of discussion. Hopkins et al.[58] defined the concept of the 'smallest worthwhile enhancement' as the value that increases the chance of victory for an athlete by 10%. Based on competition simulations, they calculated a value of 40–70% of the typical within-athlete random variation in performance between events. For the smallest worthwhile enhancement they calculated a value of ~1% for half marathon and marathon, and ~0.5% for shorter endurance distances and sprints.[58,59] Thus, it is obvious from the presented results that, in most cases, performance enhancement as a result of pre-cooling was clearly above these limits.

4.6 What is the Optimal Cooling Method?

In the discussion of pre-cooling as a worthwhile method of performance enhancement, the effort and practicability of the cooling method in a real-life setting has to be considered. The use of a cooled room (0–18°C) led to medium- to high-positive effects on performance, but this method can be regarded as relatively impractical, especially for competition, as such facilities are seldom available at competition sites (at least not for all athletes). The application of water seems to be more convenient. By reason of the effective body cooling during water immersion, this method can lead to a rapid and large reduction of core body temperature and, therefore, can strongly influence performance, but potentially, also in a negative way.[13,29,32] Thus, water temperature and duration are of importance. In contrast to this, the studies with cooling vests gave very similar results, but showed only a small or medium effect. This could have been caused by less effective cooling due to the small portion of cooled body surface. Cooling vests might be more effective if they are in contact with body parts with many cold receptors,[60] though further investigations are needed to clarify this. A similar effect as for cooling vests was found for cooling packs.[19,28,30] However, cooling packs are difficult to use during warm-up and, thus, are less practical than cooling vests.

The use of cooling vests seems to be the most feasible method, even though body temperature reduction is less effective compared with water immersion. In order to combine convenience and effectiveness, cooling with a vest could be supported by cold drink ingestion. Drinking cold beverages or ice slurries prior to exercise can have a large effect on performance.[25] However, only two studies using this method could have been included in the present analysis.[23,25] Further investigations have also shown the effectiveness of cold drinks, but these studies did not include an adequate control condition.[61,62] Thus, future research seems necessary to underline and broaden the present evidence regarding the application of cold beverages.

4.7 Is Reducing Core Body Temperature Crucial for the Performance-Enhancing Effects of Pre-Cooling?

Several groups argue that a pre-cooling-induced increase in performance demands reduced core body temperature.[18,22,26,48] However, it has been shown that pre-cooling can also positively influence performance when core body temperature remains constant[20] or is even increased.[33] Other authors claim that the observed pre-cooling effect was only due to reduced skin temperature.[24] Duffield and Marino,[21] as well as Myler and colleagues,[30] assumed reduced skin temperature to be the reason for performance enhancement, as heat transfer is improved by the increased temperature gradient between body core and skin.

In the study by Ückert and Joch,[33] core body temperature was significantly increased immediately after cooling. Nevertheless, a (medium) positive effect on performance was documented. However, in the pre-cooling condition, core body temperature decreased during exercise in contrast to the control condition. This phenomenon is also discussed in other studies and is characterized by a delayed core temperature drop during exercise after cooling.[4,29] This is probably caused by redistribution of cold blood from the body periphery to the core.[63] The effect is also known from emergency medicine. In case of hypothermia, rapid passive warming or strong movement of the patient can lead to such a decrease in temperature and even to post-rescue death.[64]

In the analysed studies, core temperature reduction after pre-cooling was usually within the range of 0–1°C. However, there is no obvious correlation between core temperature reduction and effect size. In this respect, it is noticeable that Bergh and Ekblom[13] observed a considerable performance reduction after cooling. This finding was probably caused by a core temperature reduction that was too severe (approximately 1.9°C). Thus, it might be assumed that if a certain limit for temperature reduction is exceeded, further cooling does not positively influence performance anymore but, rather, can have a detrimental effect. The existing data do not allow the delineation of such a threshold, as in another study a clear positive effect was observed, although core temperature was reduced by 1.5°C.[2]

Yeargin[34] suggested a slowed core temperature rise as another physiological mechanism of pre-cooling. This is further supported by other studies that discuss the circulation of cold blood and increased heat storage capacity of the skin to be the reason for the slowed temperature rise.[20,29]

However, other studies did not report this slowing of a rise in temperature.[2,25] Here, the authors explain the increase in performance due to pre-cooling by an increased temperature buffer until a critical core body temperature (approximately 40°C[1]) is reached. Out of the discussed studies, the two with the largest positive effect size reached a core temperature in the critical range after exercise in both conditions.[2,25] In these studies, the critical temperature was probably caused by the test protocol (open end) and high ambient temperatures. In the other open-end studies, the ambient temperature was probably too low to reach a critical core body temperature.[3,13,22,26]

It can be supposed that the location of peripheral cooling has an effect on the input provided to the hypothalamus, and thus might also influence performance. For instance, cooling of the breast could be more effective, as this body area has a large density of cold receptors. Future research into the effects of different cooling locations seems advisable to provide further insight into this aspect.

4.8 Practical Implications

The present results suggest that positive effects by pre-cooling can most likely be expected with endurance exercise. Moreover, the expected effects tend to increase with rising ambient temperature.

In order to increase performance, core body temperature or skin temperature should be reduced by cooling. With a reduction of core body temperature of up to 1.5°C, increased performance was observed in most cases. However, a reduction of 1.9°C caused a strong decline in performance,[13] suggesting that a too severe reduction may have a detrimental effect. Moreover, the working muscles themselves should not be cooled too much, as this has also the potential to reduce performance.[32,52]

With respect to the cooling method, practicability for training and competition should be the main focus beneath efficiency.[19] Additionally, to improve compliance, convenient methods are preferable. For these reasons, cooling vests present a feasible solution, as they can be worn during warm-up or halftime breaks. The cooling effect can be further increased by ingestion of cold drinks, if tolerated by the athlete.

However, based on the currently available studies it is difficult to give exact guidelines for the application of pre-cooling. This is due to the lack of uniformity of methods used in the individual studies. Different cooling protocols were combined with different types of exercise at different ambient temperatures. Therefore, for future research, it is recommended that either the cooling protocol or the exercise protocol should be standardized. For instance, a uniform cooling protocol could be chosen and its effects on different types of exercise could be investigated.

In order to achieve optimal results, athletes and coaches are advised to do their own tests during training, before they use pre-cooling during competition. It is important that these tests take place with conditions as similar as possible to the intended competition (e.g. similar ambient temperature, environment and competitive demands). Clubs and federations planning to invest in cooling methods should investigate the efficacy of the respective methods using high-quality evidence-based scientific knowledge.

From a practical as well as scientific perspective, it also seems worthwhile to analyse possible gender differences of pre-cooling. Although it seems plausible that hormonal fluctuations may affect thermoregulation, to date, only one study analysed female athletes as well, but none deliberately studied gender effects.

5. Conclusion

In most studies, pre-cooling showed a positive effect on performance. The weighted average increase of performance in the present studies was 4.9%; the weighted average effect size was 0.41. Not surprisingly, for exercise in a hot environment, the effect on performance was larger than in moderate temperatures. With respect to the type of exercise, the largest efficacy was observed for endurance exercise, whereas the effect on sprint and intermittent sprint performance was considerably smaller. In addition, for elite athletes, pre-cooling seems to have a worthwhile influence on performance. For highly endurance-trained athletes, a weighted average increase in performance of 7.7% and a weighted average effect size of 0.65 was found. In relation to the cooling method, practicality plays an important role.

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