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TITLE

Should athletes return to sport after applying Ice? A systematic review of the effect of local cooling on functional performance

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1. Abstract

Background: Applying ice or other forms of topical cooling is a popular method of treating sports injuries. It is commonplace for athletes to return to competitive activity, shortly or immediately after the application of cold.

Aim: To examine the effect of tissue cooling on outcomes relating to functional performance and to discuss their relevance to the sporting environment.

Methods: A computerized literature search, citation tracking, and hand searching were carried out up to April 2011. Eligible studies were trials involving healthy human participants describing the effects of cooling on outcomes relating to functional performance. Two reviewers independently assessed the validity of included trials, and calculated effect sizes.

Results: 35 trials met the inclusion criteria; all had high risk of bias. The mean sample size was 19. Meta-analyses were not undertaken due to clinical heterogeneity. The majority of studies used cooling durations greater than 20 minutes. Strength (peak torque/force) was reported by 25 studies with approximately 75% recording a decrease in strength immediately following cooling. There was evidence from six studies that cooling adversely affected speed, power and agility based running tasks; two studies found this was negated with a short re-warming period. There was conflicting evidence on the effect of cooling on isolated muscular endurance. A small number of studies found that cooling decreased upper limb dexterity and accuracy.

Conclusion: The current evidence base suggests that athletes will probably be at a performance disadvantage if they return to activity immediately after cooling. This is based on cooling for longer than 20 minutes which may exceed the durations employed in some sporting environments. In addition, some of the reported changes were clinically small and may only be relevant in elite sport. Until better evidence is available, practitioners should use short cooling applications and/or undertake a progressive warm up prior to returning to play.

2. Background

Applying ice or other forms of topical cooling is a popular method of treating acute sports injuries. In competitive sport, this may occur during a game, pitch-side or at half time. The premise is usually to provide reduce pain,[1] and in the absence of significant injury, athletes will often return to competitive activity shortly or immediately after the application of cold. In addition to providing pain relief, local cooling has potential to produce concomitant effects on many other physiological systems. A recent systematic review by Costello and Donnelly[2] found limited equivocal evidence on the effect that joint cooling has on proprioception (joint positional sense); as such, the authors advised caution when individuals are returning to competition immediately after cooling.

Although the analgesic effects of cooling are well established[1] these must be balanced with any potential adverse effects, to make clear recommendations for its use. Currently, there is little evidenced based consensus on how cooling may affect other physiological systems relevant to sports and exercise; a large magnitude of effect could implicate sporting performance and injury risk. Our aim was to undertake a systematic review to examine the effect of tissue cooling on outcomes relating to functional performance and to discuss their relevance to the sporting community.

3. Methods

3.1 Search Strategy

We searched MEDLINE, the Cochrane Central Register of Controlled Trials (CCTR), and EMBASE. 18 Medline subject headings (MeSH) or key words were combined. Results were limited human subjects, and subject headings were modified for use in CCTR and EMBASE. Each database was searched from their earliest available record up to April 2011. We also searched Current Controlled Trials and the World Health Organisation (WHO) International Clinical Trials Registry for ongoing and recently completed trials, undertook a related articles search using on Pubmed (http://www.ncbi.nlm.nih.gov/pubmed) and read reference lists of all incoming articles. English language restrictions were applied.

3.2 Inclusion criteria

No restrictions were made on study design or comparison group**.** Studies must have involved human participants treated with a local cooling intervention. Interventions using whole body cooling eg. cold water immersion above the waist or whole body cryotherapy (WBC) using an environmental chamber, or other forms of cold air cooling were excluded. Studies must have reported at least one outcome relating to functional performance (eg. muscle strength, power, speed, agility, accuracy movement), measured both before after cooling intervention. Studies measuring strength or force production during evoked muscle contractions were not considered.

3.3 Selection of studies

Two authors independently selected trials for inclusion (CB, PG). The titles and abstracts of publications obtained by the search strategy were screened. All trials classified as relevant by either of the authors were retrieved. Based on the information within the full reports, we used a standardised form to select the trials eligible for inclusion in the review. Disagreement between the authors was resolved by consensus, or third party adjudication (JC).

3.4 Data extraction and management

Data were extracted independently by two review authors using a customised form (CB, JC). This was used to extract relevant data on methodological design, eligibility criteria, interventions (including detailed characteristics of the cooling protocols), comparisons and outcome measures. Any disagreement was resolved by consensus, or third party adjudication (PG). To perform intention-to-treat analysis, where possible, data were extracted according to the original allocation groups, and losses to follow-up were noted. There was no blinding to study author, institution or journal at this stage.

3.5 Measures of treatment effect

For each study, mean differences (MD) or standardised mean differences (SMD) and 95% confidence intervals (CIs) were calculated for continuous outcomes using RevMan software. Treatment effects (MD, SMD) could be based on between group comparisons (ice vs control) using follow up data, and/or within group comparisons (pre ice vs post ice). When standard deviations were missing from continuous data, studies were scanned for any other statistics (confidence intervals, standard errors, T values, P values, F values) that allow for its calculation. There were no cases were large numbers of standard deviations were missing.

3.6 Risk of bias

For all included studies, methodological quality was assessed by two authors independently (CB, JC), using the Cochrane risk of bias tool.[3] Each study was graded for the following domains; sequence generation, allocation concealment, blinding (assessor), and incomplete outcome data. For each study, the domains were described as reported in the published study report (or if appropriate based on information from related protocols, or published comments) and judged by the review authors as to their risk of bias. They were assigned ‘Low’ if criteria for low risk of bias are met or 'High' if criteria for high risk of bias are met. If insufficient detail of what happened in the study was reported, or if what happened in the study was known, but the risk of bias was unknown, then the risk of bias was deemed 'Unclear' for that domain. Disagreements between authors regarding the risk of bias for domains were resolved by consensus.

3.7 Subgroup analysis

Differences in study quality and details of the treatment intervention (e.g. duration of cooling, time period between cooling cessation and follow up assessment), were regarded as a potential source of bias and considered for subgroup analysis.

4. Results

Figure I summarises the search strategy and selection process based on included and excluded studies.

Insert Figure I

4.1 Included studies

Characteristics of included studies are summarised in Table I. There were 35 eligible studies,[4-38] comprising a total of 665 healthy participants. The average sample size was 19 with the largest study based on 89 participants. Participants tended to be young and mean ages ranged from 19 [19] to 32 years; [26] one study[36] included a subgroup of elderly participants (>70 years).

Insert Table I

Twenty-seven studies (n=3 randomised controlled trials, and n=24 cross over trials) incorporated a cooling group and a resting control condition. In cross over studies the time between conditions ranged from one day, up to 14 days. The remaining eight studies were observational and measured outcomes before (baseline) and after cold application. The duration of cooling ranged between 3 and 45 minutes. All but seven studies[13,22,25,26,28,29,34] applied cooling for at least 20 minutes. Two[25,34] included a comparison of different cooling durations and three,[7,21,36] cooled until pre-determined intra-muscular (I/M) temperature reductions were reached (~30° I/M temperature). A total of 15 studies recorded the tissue temperature reductions associated with cooling. Eight recorded skin temperature[11,13,17,24,25,27,35,38] with the lowest values reported in individual studies ranging from ~11.9°C[38] to 22.5°C.[13] Seven recorded I/M temperatures[4,7-9,12,21,36] with lowest values ranging between 23°C[9] and 30.4°C.[7]

4.2 Details of outcomes

Twenty five studies recorded muscle strength.[4-9,11-15,18,20-24,26-30, 35,36,38] The majority used an isokinetic dynamometer to measure peak force (N) or torque (Nm) at isolated body regions: knee extension, elbow flexion and ankle (all movements). The remainder used a cable tensiometer[8,22] or a strain gauge device or load cell[4,11,35,38] with one[21] failing to specify the recording device. Eight studies[5,6,9,10,13,26,29,35] measured grip strength using a hand grip dynamometer; three further studies measured isolated finger strength[11] or hand dexterity.[25,35] Nine studies assessed endurance based on the total work [14,15,20] or time to fatigue[4,9,10,22,27,29] undertaken during multiple exercise repetitions.

Six studies examined the effect of cooling immediately prior to undertaking various types of whole body exercise tests. These included vertical jump height[19,31] or power,[33,37] timed hop test,[19] sprint time[31,33] and the time taken to complete various running based agility tests eg. caricoca runs,[16] shuttle sprints,[16,19,31,34] T-Shuttle[33] or co-contraction test.[16,34] Two studies recorded performance accuracy during throwing (% of ball throws to hit a target in 30 seconds)[32] and shooting (total shooting score)[17] and two[25,35] measured hand dexterity.

4.3 Follow up

All studies recorded outcomes before and immediately after cooling. Eleven studies undertook additional outcome assessment at 5,[29,38] 7,[33] 10,[22,29] 12,[33] 15,[26, 37, 38] 17,[33] 20,[31,34] 22,[33] 27,[33] 30,[8,38] 32,[33] 45,[38] 60,[8,38] 90,[8] 120[8] and 180[8] minutes post treatment. Additionally both Johnson[5] and Coppin[6] repeated the assessment of grip strength every 20 minutes for 4 hours post treatment.

4.4 Risk of bias

There was a high risk of bias across all studies as summarised in Figure II. 15 studies stated that participants were randomised into groups, however only two[8,24] provided adequate details on how the random sequence was generated. There was further risk of selection bias as just one randomised study[24] adequately reported allocation concealment. Blinding of outcome assessor was not reported in any study. Due to the nature of the intervention we did not assess blinding of participants or care givers. There was a high risk of attrition bias across all studies; only four studies[6,22,33,37] provided any information relating to drop outs, exclusions, missing data or approach to analysis.

Insert Figure II

4.5 Muscle Strength: Lower limb (thigh)

Eight studies focused on quadriceps strength. Howard et al.[15] found that a 45 minute cold water immersion resulted in significant strength reductions during knee extension with the largest changes observed during high speed isokinetic test speeds (180°/sec-400°/sec); peak torque, average power and total work were all reduced by up to 27% compared with baseline values. Three studies[7,21,36] recorded a number of knee extension strength outcomes after inducing a range of intra-muscular temperature reductions. Zhou et al.[21] found peak knee extension force decreased when quadriceps muscle temperatures were cooled below 34°C, with further decreases when muscle temperatures of 30°C were reached (MD 126.80 N [95% CI: -1.38 to 254.98] vs baseline). Dewhurst et al.[36] found that colder intramuscular temperatures (~30°C) were associated lower isokinetic torques, however this was only observed in a sub-group of younger participants. Bergh and Ekblom[7] reported that for every 1°C decrease in intramuscular temperature, both extension torque and power declined by around 5%. A small study[12] found that compared to untreated control, a 45 minute cold water immersion (12°C or 18°C) involving the lower limbs decreased isokinetic cycling performance in terms of peak force (MD 143 Newtons [95% CI -19.36 to 305.36]) and peak power output (MD 278 Watts [95% CI -9 to 565]). Others reported more moderate changes. Thornley et al.[27] found little to no differences in knee extension torque immediately after treatment when groups were treated with hot and cold packs at a range of temperatures; of note the cold group had the largest reduction from baseline (MD 19 Nm 95% CI -25.96 to 63.96). In contrast, Sanya and Bello[22] found that 30 minutes of thigh cooling increased isometric quadriceps strength (MD 5.89 kgf [1.88 to 9.9]). Catlaw et al.[18] also found higher eccentric strength during knee extension after cooling; this was measured over a range of test speeds with the largest between group differences occurring at 175°.s^{-1} (MD 40Nm [95% CI: 280.8 to 51.62] vs control).

Muscle strength: Lower limb (calf/ankle)

A 20 minute cold water immersion of the lower limb significantly decreased plantar flexion peak torque (MD 10 ft lbs [95% CI -2.1 to 22.1] vs control).[14] Kubo et al.[30] used a more intense intervention on the entire lower leg (30 minute cold water immersion at 5°C), and reported similar decreases in ankle plantar flexion peak torque immediately after cooling (MD 9.30Nm [95% CI: -5.02 to 23.62] vs baseline). Using a different measuring device, Pereira et al.[38] reported decreased plantar flexion torque (MD 37 N 95% CI: -43.14 to 117.14 vs baseline) after a 30 minute crushed ice pack on the antero-lateral musculature.

Hatzel et al.[23] recorded a wide spectrum of strength outcomes at the ankle (concentric and eccentric peak torque, in plantar flexion, dorsiflexion, eversion and inversion) before and after a 20 minute cold water immersion, however the only significant finding was a decrease in concentric dorsiflexion immediately after cooling (MD 7.4 N/m [95% CI: 14.93, -0.13 to 14.93] vs baseline). Hopkins et al.[24] found that a 30 minutes ice pack application to the lateral ankle joint induced small increases in plantar flexion peak torque, compared to a resting control. Using a similar design, Kimura et al.[20] also found that a 30 minute cold water immersion resulted in small increases in eccentric ankle plantar flexion peak torque (MD 3.93 Nm [95% CI: -12.23 to 20.09])

Muscle strength: Upper limb

Borgmeyer et al.[28] found that 10 minutes of biceps cooling had little effect on concentric or isokinetic strength at the elbow (MD 0.4 Nm [95% CI -1.45 to 2.25] vs control). Five studies found that long durations (>30 minutes) of upper limb cold water immersion, significantly decreased isolated finger strength[11] and hand grip strength.[5,6,9,35] There was sufficient data for effect size calculation in just one of these studies (MD 4.10 kg [95% CI: -9.66 to 17.86] vs control),[9] with one other[35] stating that grip strength was reduced by 12%. Three further studies[13,26,29] were based on shorter periods of cooling (<10 minutes) of the hand and/or forearm; both Douris et al[26] (MD: 129N [95% CI: 121.16 to 136.84]) and Vincent and Tipton[13] (decreased by 13-16%) found significant reductions in peak grip strength compared to pre-cooling values, whereas, Hamzat and Fatudimu[29] found little to no change in grip strength immediately following an ice towel application (MD 0.36 Newtons 95% CI -2.21 to 2.93) vs baseline].

4.6 Muscle endurance

Kimura et al.[20] reported that a 30 minute cold water immersion significantly increased plantar flexion endurance (total work during 100 repetitions) (MD 377.82Nm [95% CI: -158.03 to 913.67]) compared to a resting control condition. Three studies also found that cooling significantly increased isometric endurance based on time to fatigue at the quadriceps[22,27] or hand grip muscles;[29] the magnitude of the changes were much larger in Thorley et al.[27] (MD 26.4 secs [-1.61 to 54.41] vs heating) compared to both Sanya and Bello[22] (MD 4.08 secs [-0.88 to 9.04] vs baseline) and Hamzat and Fatudimu[29] (MD 5.04 secs [95% CI 1.08 to 9] vs baseline).

In contrast, both Petrofsky and Lind[9] and Barter and Freer[10] found cold water immersion reduced time to grip strength fatigue compared to neutral water immersion; the magnitude of effects differed across each study (MD 293 secs [95% CI: 132.96 to 453.04])[9] (MD 0.8 secs [95% CI: -6.22 to 7.82]).[10] Mattacola and Perrin[14] also reported reduced endurance after cooling ankle plantar flexors (MD 45 ft lbs [95% CI -4.92 to 94.92] vs control); a small study by Edwards et al.[4] concluded quadriceps endurance was optimised at immersion in water at 26°C but tended to decrease after immersions at extreme temperature (either 10°C or 44°C). In a further study[15] long durations (45 minutes) of cooling did not affect isokinetic quadriceps muscle work, over a range of test speeds.

4.7 Vertical jump; sprint and agility performance

All studies[19,33,34,37] found that vertical jump performance was reduced immediately after cooling; this was observed after 10 minutes of crushed ice applied to the hamstrings (MD 1.10cm [95% CI -1.96 to 4.16] vs baseline),[34] 20 minutes of lower limb cold water immersion in 13°C (MD 2.14cm [95% CI: -3.54 to 7.82] vs baseline)[19] or 20 minutes of lower limb cold water immersion in 10°C (MD 648 Watts [95% CI 10.91 to 1285.09]).[33] The largest detriments in vertical jump performance were found following a 45 minute cold water immersion involving both lower limbs (MD 1165 Watts [95% CI: 194 to 2135.76] vs baseline).[37]

There was also a clear trend [19,31,33,34] that shuttle run time was worse immediately following cooling; the largest change from baseline was based on a MD of 0.63 seconds (95% CI: 0.27 to 0.99).[33] There was further evidence that after 10-20 minutes of lower limb icing, participants took longer to complete various running based agility tests;[16, 31,33, 34] the largest reported MD from baseline was 1.38 seconds [95% CI 0.72 to 2.04].[33]

4.8 Performance Accuracy

There was evidence from a single observational study[32] that 20 minutes of shoulder joint cooling, significantly reduced throwing accuracy (MD 7.11% [95% CI: 2.29 to 11.93] vs baseline). In contrast, a small study by Lackie et al.[17] found that compared to control, isolated forearm immersion (30 minutes at 10°C) decreased tremor by 40% during shooting performance and improved scoring accuracy (SMD 0.89 95% CI -0.32 to 2.10).

4.9 Upper limb dexterity

Cheung et al.[25] showed that short duration (300 secs) immersions of the hand and forearm significantly reduced hand dexterity in terms of time to complete a functional dexterity test (MD 9 secs [2.89 to 15.11] vs control) and Perdue Peg Test (8.8 points [3.93 to 13.67] vs control). Chen et al.[35] also concluded that hand immersion reduced gross and fine finger dexterity by up to 55% (vs baseline).

4.10 Summary of immediate effects of Cooling

We were unable to combine studies for meta-analyses due to heterogeneity relating to cooling time/dosage, body part and outcome measure. The overall trend was a reduction in performance immediately after cooling. This is evident in the forest plot graphs (SMD [95% CI]) presented in Figure IV and V which summarise the within (baseline vs post ice) and between group differences (ice versus control).

Insert Figures III and IV

4.11 Duration of effects post cooling

Two studies,[5,8] found that over a 2-4 hour period post cooling, strength values steadily increased beyond baseline levels. The remainder of studies noted that cold induced detriments in performance lasted beyond the immediate stages after cooling, but for varying durations. Pereira et al.[38] found that a 5 minute rest period was enough for ankle D/F strength to return to baseline; whereas two studies[22,29] found performance remained significantly changed for up to 10 minutes post cooling. In another study,[26] the effects of cold on grip strength diminished with time, however a 5.9% strength reduction (from baseline) remained 15 minutes post cold water immersion. Coppin et al.[6] reported that grip strength remained below baseline values for up to 40 minutes post immersion. Fischer et al.[34] found vertical jump performance was still below baseline values after a 20 minute recovery. Patterson et al.[2008] also found that vertical jump, agility and sprint performance remained lower than baseline for up to 30 minutes following treatment. Similarily Richendollar et al.[31] also found that vertical jump, agility and sprint performance were all reduced for 20 minutes after cooling. However, both Richendollar et al.,[31] vertical jump, agility and sprint performance, and Dixon et al.,[37] counter movement jump, found these detriments were negated after undertaking a progressive warm up for 6.5 and 15 minutes respectively.

4.12 Cooling dose

Two studies[25,34] incorporated different cooling durations. Fischer et al.[34] found that although 10 minute treatments reduced vertical jump and agility/speed performance, no effects were reported when treatment times were reduced to 3 minutes. In a comparison of three different cooling times (30, 120 or 300 secs), Cheung et al.[25] also found that longer durations induced larger detriments to hand dexterity.

4.13 Adverse effects

No study reported cold induced complications or side effects relating to skin damage, nerve palsy, or allergy. One participant suffered a hamstring strain during a baseline (pre-cooling) 40 m sprint test.[33]

5. Discussion

5.1 Quality of evidence

There were large limitations within the current evidence base. Sample size was generally small, raising questions as to the power of individual trials. There was also a consistently high risk of bias across the studies, and we were unable to meaningfully sub-group studies into high and low quality. Few studies reported adequate sequence generation or allocation concealment. As some of the included studies were randomised cross over trials there may also be risk of carry over effects. Primarily this could relate to a practice or learning effect during the outcome assessments. Additional carry over effects may also have resulted from fatigue induced during the first treatment period; the length of time between cross over conditions varied from the same day[25] up to 2 weeks[20] across studies. In a number of the cross over trials,[9,11-15,36] the length of time between treatment conditions was not stated.

It is acknowledged that based on the nature of cold treatment, stringent blinding of participants and caregivers is difficult. Blinding of outcome assessors should be feasible but was not reported in any of the included studies. Equally no studies adequately described missing outcomes or how these were managed. Overall, the consistently small sample sizes and poor quality of evidence mean that findings should be interpreted with caution.

5.2 Muscle strength

Basic scientific evidence portends that cooling is detrimental to muscle performance based on cold induced decreases to: nerve conduction velocity,[39] receptor firing rate,[40] muscle spindle activity,[41] myotatic stretch reflex, and ion (Na^+, K^+, Ca^{2+}) diffusion at the motor end plate.[42] It is also well accepted that enzymatic activity is reduced at lower temperatures, and there are further suggestions that cooling impairs Ca^{2+} release from the muscles' sarcoplasmic reticulum, resulting in a decline in ATP availability and impaired cross bridge function.[11,43]

The trend from the current evidence base was that cooling reduces muscle strength. The magnitude of these changes was variable however. In some cases large effects were reported based on strength reductions from baseline of 13%[13] to 27%,[15] or peak torque losses of around 130N.[12, 21, 26] In others, cold induced strength losses were less than 9 Nm;[23, 28, 29, 30] such changes may be less clinically relevant and may only be applicable to elite sport environments. Although a small number of studies found cold induced increases in force output;[8,18,20,22,24] the magnitude of these changes were consistently small. Interestingly, one of these studies[24] applied ice directly onto the ankle joint; isolated joint cooling has previously been shown to enhance muscle recruitment based on H-reflex and central activation ratios at the ankle and knee.[44,45]

5.3 Muscle endurance

The effects of cooling on other components of muscle function were conflicting; there were some suggestions towards cold induced increases in muscle endurance [14,15,20,22,27,29] with others showing an opposite effect.[4,9,10,] Some postulate that cooling muscle prior to intense exercise, decreases pain, minimises metabolic by products[46] or prevents excessive increase in muscle temperature.[20] Furthermore a recent review[47] found that pre-cooling using ice vests, ice collars or body immersions, improves aerobic performance during running and cycling. The theory is that pre-cooling prevents excessive increases in core body temperature during exercise. The effect of core temperature on our current findings is difficult to ascertain as no included studies measured core temperature. Of note, interventions in the current review used local muscle cooling or peripheral limb immersion; previous studies (Palmieri, to insert ref) found that such localised cooling does not affect core temperature.

5.4 Vertical jump; sprint and agility performance

The lower limb performance outcomes recorded in some of the included studies may be better correlates of sports performance. Five [19,31,33,34,37] found cooling had a negative effect on at least one of the following outcomes: vertical jump, sprint or agility, with only Evans and colleagues [16] reporting no changes. Vertical jump height was reduced by up to 2 cm in the immediate stages after cooling.[19,34] The majority also found that sprint or agility time was reduced by around 0.2 seconds, with one study[33] noting larger decreases of 1.4 seconds. The clinical relevance of these detriments may again depend on the type of sport or performance level and how soon following treatment individuals return to participation.

A small number of studies recorded skill based outcomes. There was a general trend that cooling decreased hand dexterity, and throwing accuracy by approximately 7%. In contrast, a small study[17] found that cooling enhanced shooting performance in novices; this was attributed to a cold induced attenuation of physiological tremor (up to 40%) which was measured using an accelerometer.

5.5 Cooling dose, return to sport and warm up

In the current review there was variation across studies in the cooling modes, durations and body areas treated. Overall, the cooling dosages were large with most studies using a minimum duration of 20 minutes. Indeed, many studies [4,7-9,12,21,36] induced intramuscular temperatures to less than 30°C. It is difficult to recommend an optimal tissue temperature reduction. Recent clinical guidelines[1] suggest that cooling dose should be modified according to the patho-physiological objective. Longer bouts of cooling, such as those employed within the current review, may be most appropriate for targeting deep tissue and/or reducing local cellular metabolism. In contrast, local analgesia, which is often the objective prior to returning sport, may be readily attained with shorter durations (<10 minutes).[1] The patterns in the current review may therefore represent the largest potential changes associated with cooling. We must also consider that during sport, very brief bouts of cooling (<1 min) are sometimes used during a break in play, where the rationale is to provide a counter irritant for pain, rather than to induce large/deep temperature reductions. Interestingly one study[34] found that a 3 minute treatment did not affect vertical jump, agility or sprint performance.

We noted that the majority of studies in this review involved CWI or muscle cooling. Localised joint cooling may have different effects on function; indeed, evidence exists that isolated joint cooling [44,45] has an excitatory effect on the surrounding musculature. This could have positive implications and future studies must consider the effect of isolated joint cooling on functional performance. Clinicians should also consider that outcome is affected by individual factors such as adiposity, with higher levels acting to limit the magnitude and depth of cooling.

It be important that intra-muscular temperatures have been shown to decline for up to 10 minutes after ice pack removal.[48] In the current review, many studies found that performance remained below baseline for at least fifteen minutes following treatment. In sport, athletes are often encouraged to undertake a warm up period between finishing cooling and returning to play. Previous studies have shown that light or moderate physical activity can significantly speed up intra-muscular re-warming.[48,49] We also found evidence from two studies[31,37] that there were no performance detriments when participants undertook a 6.5-15 minute warm up (dynamic joint movements and jogging) between finishing cooling and returning to activity. Future study should ascertain whether this practice should be universally encouraged prior to returning to sport. Although it seems likely that the physiological effects of cooling can be reduced through use of a progressive warm up, again we must consider that these studies applied cooling for 20[31] to 45 minutes.[37] The significance of a post icing warm-up may depend on the magnitude and depth of tissue cooling and may be less important after short cooling durations.

5.6 Comparison to other reviews

Few reviews have systematically examined the effect of cooling on other physiological systems relevant to sporting activity. Costello and Donnelly[2] found equivocal evidence on the effect that joint cooling has on proprioception (joint positional sense), and in conjunction with the current review, the majority of included studies were of limited methodological quality. They did find some significant effects; absolute errors were found to increase (worsen) by 1-2 degrees immediately after cooling the ankle and shoulder joints. Again the effect of these changes on performance and injury risk is difficult to determine.

Although the current review focused on a healthy population, other reviews[1,50] have noted a dearth of high quality randomised studies into the therapeutic effect of cooling after soft tissue injury. Quod et al.[51] and more recently Ranalli et al.[46] have also reviewed the effects of pre-cooling before exercise on subsequent endurance performance in the heat and aerobic and anaerobic performance respectively. Both reviews concluded that pre exercise cooling seems to have a positive effect on aerobic performance, although the impact on anaerobic performance varied and did not provide the same positive effect.

5.7 Limitations and future study

We undertook an exhaustive search based on a comprehensive list of electronic databases and extensive supplementary searching. We acknowledge that other relevant studies may have been overlooked in the grey literature. None of the included studies had a registered protocol, and bias from selective reporting of results, was therefore difficult to ascertain. There were a limited number of outcomes where summary values were extracted from graphs. Although this was undertaken by two independent reviewers, with inconsistencies checked through reviewer consensus and a third party, it is still serves as an estimation of treatment effect. We were also unable to perform any paired analysis in the randomised cross over studies; instead data were analysed as if these studies used a parallel group design. This approach may give rise to bias through unit of analysis error; however this is likely to be conservative, as the cross over studies tend to be under rather than over-weighted.[54]

Future studies must incorporate larger sample sizes, and employ methods to limit selection, performance and attrition bias. Employing short duration cooling may be more practically relevant, particularly if they are applied in the middle of simulated play; this would better ascertain the influence of cooling when the physiological systems (eg. blood flow, neural activity, and metabolism) are functioning under competitive conditions. This review is limited to healthy subjects whereas in real sporting situations, ice is usually applied to athletes in pain. Replicating painful circumstances in the laboratory may be more practically relevant and creates a challenge for future studies. Finally, we have focused on important outcomes relevant to sporting performance; however we acknowledge that other key correlates of performance exist. There is evidence that temperature can influence sensori-motor patterns[52] and soft tissues' visco-elastic properties[53] which should be systematically examined in future reviews.

6. Conclusion

The current evidence base suggests that athletes' performance will probably be adversely affected should they return to activity immediately after cooling. We must consider that these findings are largely based on cooling durations of at least 20 minutes which may exceed the dosages used on the sidelines or at half time during sport. There is preliminary evidence that cold induced detrimental effects on performance can be reduced or prevented by using a shorter cold application and/or undertaking a progressive warm up prior to returning to play. Future studies in this area must incorporate larger sample sizes, and limit risk of bias. The cooling dosages employed should be made more applicable to the sporting environment with potentially more focus on short duration applications. Until better evidence is available, practitioners should use short cooling applications and/or undertaking a progressive warm prior to returning to play.

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8. Table I

Study Characteristics

AUTHOR REF [STUDY TYPE]	PARTICIPANTS	INTERVENTION	TISSUE TEMPERATURE IMMEDIATELY POST ICE	OUTCOMES RECORDED [FOLLOW UP]	SUMMARY OF SIGNIFICANT EFFECTS OF COOLING AT IMMEDIATE FOLLOW UP	DURATION OF EFFECTS
Edwards [4] [Observational]	N=10 healthy Mean age: 25.3 (± 3.5 yrs)	-CWI, at a range of temperatures (10-44°C) 45 minutes (leg up to ischial tuberosity)	Lowest I/M temperature 22.5°C	ISOMETRIC KNEE EXT STRAIN GAUGE 1. Endurance (time to fatigue, secs) [immediately post Rx]	No significant findings	N/A
Johnson [5] [Cross over]	N=12 healthy	-CWI , 30 mins (forearm immersion) -Rest, 30 mins	Not assessed	HAND GRIP DYNAMOMETER 1.Grip strength [Immediately, every 20 minutes for 4 hours post Rx]	1 DECREASED[ab]	1 INCREASED[ab] **b**etween 80-240 minutes post Rx
Coppin [6] [RCO]	N = 13 healthy Aged: 22-52 yrs 9 male 4 female	-CWI at 10°C, 30 mins (left forearm immersion) - CWI at 10°C, 30 mins (right forearm immersion) -Rest 30 mins	Skin temperature measured but changes not reported.	HAND GRIP DYNAMOMETER 1. Grip strength (kg) [Immediately, every 20 minutes for 4 hours post Rx]	1 DECREASED[a]	Hand grip strength returned to baseline after 40 mins
Bergh [7] [RCO]	N=5 healthy males	-CWI until various I/M temperatures induced (30-39°C)	Lowest I/M temperature 30.4°C	ISOKINETIC DYN KNEE EXT CONC (0,90, 180°/sec) 1. Peak torque (Nm) 2. Power (W) 3. Vertical jump (height, cm) 4. Sprint performance: cycle (power, W) [immediately post Rx]	Cooling decreased performance based on correlations between muscle temperature and 1-4.	N/A
Oliver [8] [RCO]	N=20 healthy 8 male mean age: 29.2 yrs 12 female mean age: 25.1 yrs	- CWI at 10-12°C, 30 min (lower leg immersion) -Rest 30 min	25.5°C (at I/M depth=radius of muscle cross-sectional area)	ANKLE Isometric P/F CABLE TENSIOMETER 1. Peak force: (kg) [immediately post Rx, 30, 60, 90, 120, 180 mins post Rx]	No significant findings	1 INCREASED[ab] **b**etween 60-180 minutes post Rx
Petrofsky [9] [Cross over]	N=10 healthy 5 male, mean age: 24.3 (± 1.9 yrs) 5 female, mean age: 22.1 (± 2.7 yrs)	-CWI, 10°C -CWI, 20°C -CWI, 30°C -CWI, 40°C All: 30 minute, hand and forearm immersion	Lowest I/M temperature ~23°C	HAND GRIP DYNAMOMETER 1. Strength (kg) 2. Endurance (grip hold, secs at 15%, 40% and 70% of MVC) [immediately post Rx]	1 and 2 DECREASED[b] (vs 20°C)	N/A
Barter [10] [Cross over]	N=12 healthy males Aged: 19-25 yrs	- CWI at 18°C, 30 min -HWI at 45°, 30 min -Neutral immersion at 37°, 30 min	Not assessed	HAND GRIP DYNAMOMETER 1. Time to fatigue (at 70% MVC secs)	No significant differences (CWI vs controls) Note: HWI significantly	N/A

		ALL (hand and forearm immersion)		[immediately post Rx]	DECREASED 1 vs neutral	
Ranatunga [11] [Cross over]	N=4 healthy	-CWI at 25-45°C (hand immersion)	Skin temperature <20°C	INDEX FINGER ABD TENSION TRANSDUCER 1. Peak tension (% baseline) [immediately post Rx]	1 DECREASED[a]	N/A
Sargeant [12] [Cross over]	N=4 Active, but untrained 1 female, 24 years 3 male, 27.67 (± 5.51)	-CWI at 12°C, (to the level of the gluteal fold), 45 mins -CWI at 18°C, (to the level of the gluteal fold), 45 mins -CWI at 44°C, (to the level of the gluteal fold), 45 mins -No immersion- room temperature	Muscle temperature reduced by 7.7°C in 12°C water compared to no immersion condition	ISOKINETIC CYCLE ERGOMETER (20s maximum sprint at a constant rate of 95 crank rev/min) 1. Peak force (N) 2. Peak power (W) 3. Maximal mean power (W) (Immediately after Rx)	1, 2 and 3 DECREASED[b] (vs no immersion)	N/A
Vincent [13] [Cross over]	N=12 healthy Aged: 20-42 yrs	-CWI at 5°C, 2 mins x 5 (Hand immersion) - CWI at 5°C, 2 mins x 5 (forearm immersion only)	Skin temperature reduced by ~22-23°C	HAND GRIP DYNAMOMETER 1. Grip strength (N) [immediately post Rx]	1 DECREASED (both groups)[a]	N/A
Mattacola [14] [RCO]	N=16 healthy 5 male, 11 female Mean age: 22.1 years	-CWI at 15°C, 20 mins (lower leg immersion) -Rest 20 mins	Not assessed	ANKLE P/F (ROM 0-50°) ISOKINETIC DYNAMOMETER 1. Peak torque (Nm) 2. Average power (Nm) 3. Total work (Nm) [immediately post Rx]	1, 2 and 3 DECREASED[b]	N/A
Howard [15] [RCO]	N=10 physically active males Mean age: 22.9 (± 2.2 yrs)	-CWI at 12°C, 45 mins (lower limb immersion to gluteal fold) -Immersion at 35.5°C, 45 mins (lower limb immersion to gluteal fold) -Non-immersion, 45 mins (room temperature 22-23°C)	Not assessed	KNEE EXT ISOKINETIC DYNAMOMETER 1. Peak torque, 2. Time to peak torque, 3. Angle of peak torque 4. Average power, 5. Total work (Velocities of 0, 30, 180, 300 400°.sec^{-1} randomly chosen) 6. Peak torque Isometric (45° angle) [immediately post Rx]	1,4, 5 and 6 DECREASED (at 180, 300 400°.sec^{-1})[b] (vs neutral immersion and non immersion)	N/A
Evans [16] [RCO]	N=24 healthy Mean age: 22.4 (± 2.1yrs)	-CWI at 1°C, 20 min (lower limb immersion up to 8cm above malleolus) -Rest 20 min	Not assessed	LOWER LIMB TIME TO COMPLETE TEST (secs) 1. Shuttle run 2. Co-Contraction agility 3. Carioca run agility [immediately post Rx]	No significant findings	N/A

Lakie [17] [Cross over]	N=6 healthy 5 male, 1 female Mean age: 24.8 yrs	-CWI at 10°C, 30 mins (forearm only) -HWI at 44°C, 30 mins (forearm only) -Control, no immersion	Skin temperature 22.5°C	SHOOOTING PERFORMANCE ACCELEROMETER 1.Tremor (frequency, size and power) 2. Final score (/200) [immediately post Rx]	1 DECREASED[b] (vs control and HWI)	N/A
Catlaw [18] [Cross over]	N=16 healthy 8 male, 8 female Mean age: 20.4 (± 1.2 yrs)	-Cryocuff, 20 mins (thigh) -No ice	Not assessed	KNEE EXT ISOKINETIC DYNAMOMETER 1. ECC Peak Torque 2. CONC Peak Torque (Velocities of 25-200°.sec^{-}) [Immediately post Rx]	1 DECREASED (at 175 and 200°.sec^{-})[b]	N/A
Cross [19] (RCT)	N= 20 healthy Mean age: 19.3 (± 1.2 yrs)	- CWI at 13°C, 20 mins (lower limb immersion up to fibular head, with water turbulence) - Rest, 20 min	Not assessed	LOWER LIMB 1. Hop test (time to complete, sec) 2. Vertical jump height (cm) 3. Shuttle run (time to complete, sec) [immediately post Rx]	2 DECREASED[a] AND 3 INCREASED[a]	N/A
Kimura [20] [RCO]	N=22 healthy 11 male, 11 female Mean age: 23.8 (± 3.5 yrs)	-CWI at 10°C, 30 min (lower limb immersion to mid thigh) - Rest 30 min	Not assessed	ANKLE P/F ECC ISOKINETIC DYNAMOMETER 1. Peak Torque (Nm) 2. Total work (Nm) [immediately post Rx]	2 INCREASED[b]	N/A
Zhou [21] [Observational]	N=3 healthy males Mean age: 31yrs	-Ice bag applied until thigh IM temperature reached 30°C	30° (at 30 mm IM depth)	KNEE EXT ISOMETRIC 1. Peak force (N) [immediate post Rx]	1. DECREASED[a]	N/A
Sanya [22] [Observational]	N=60 healthy 30 male, 23.43 (± 1.89 yrs) 30 female, 22.63 (± 1.71 yrs)	-Ice towel application at 3-6°C, 5 mins (included liquid paraffin, applied to the anterior aspect of the thigh)	Not assessed	ADAPTER CABLE TENSIOMETER 1. Isometric quadriceps strength (kg/f) 2. Endurance index (sec) [immediately, 10 mins post Rx]	1 INCREASED 2 INCREASED (male only)	1 remained increased at 10 mins post Rx
Hatzel [23] [Observational]	N=20 healthy Mean age: 19.6 (± 1.3 yrs)	-CWI at 10°C, 20 min (lower limb immersion to tibial plateau)	Not assessed	ANKLE ECC and CONC ISOKINETIC DYNAMOMETER 1. Peak Torque: (Nm) a: PF ; b. INV; c. EV; d. DF [immediately post Rx]	1d Conc DECREASED[a]	N/A
Hopkins [24] [RCT]	N=30 healthy 16 male, 14 female Mean age: 21 (± 3yrs)	- 1.5L of crushed ice, 30 minutes (lateral ankle joint) - Rest, 30 min	Final skin temperature approx. 16°C	ANKLE P/F CONC ISOKINETIC DYNAMOMETER 1. Peak torque: (Nm) [immediately post Rx]	1 INCREASED[b]	N/A

Cheung [25] [Cross over]	N=16 healthy 11 male, 15 female Mean age: 24.8 (± 9.4yrs)	-CWI at 10°C, (immersion to lateral epicondyle), 30 secs -CWI at 10°C, (immersion to lateral epicondyle), 120 secs -CWI at 10°C, (immersion to lateral epicondyle), 300 secs -No immersion	Final skin temperature 15 (+/- 0.4°C)	HAND DEXTERITY TESTING 1. Buckle test (time to complete, secs) 2. Fine dexterity [immediately post Rx]	1 INCREASED[b] (120 sec and 300 secs vs control) 2 DECREASED[b] (300 sec vs control)	N/A
Douris [26] [Cross Over]	N=16 healthy Mean age: 32 (± 6.3 yrs),	-CWI at 10°C, 5 minutes (elbow, forearm and hand immersion)	Not assessed	HAND DYNAMOMETER 1. Grip strength: Isometric (lbs) (immediately, 15 min post Rx)	1 DECREASED[a]	1 remained DECREASED[a] at 15 minutes post Rx
Thornley [27] [RCO]	N=9 healthy males Mean age: 22 (± 3 yrs)	-Hot pack 55°C -Warm pack 34°C -Neutral pack 22°C -Cold pack -17°C All: 30 mins, anterior thigh	Skin temperature: 12.4 (+/-2.8)	KNEE EXT ISOMETRIC 1. Peak torque (Nm) 2. Time to fatigue (secs) [immediately post Rx]	2 INCREASED[b] (vs hot and warm pack)	N/A
Borgmeyer [28] [RCO]	N=11 healthy males Mean age: 20.9 (± 1.1 yrs)	-Ice massage, 10 min (biceps) - Rest, 10 min	Not assessed	ELBOW FLEX CONC ISOKINETIC DYNAMOMETER 1. Peak torque: (Nm) (immediately post Rx)	No significant findings	N/A
Hamzat [29] [Observational]	N=89 Healthy 49 male, 40 female Aged 19-30yrs	-Ice towel application, 10 mins (included liquid paraffin, applied to the forearm muscles, temperature not stated)	Not assessed	HAND DYNAMOMETER 1. Grip strength: Isometric (kgf) 2. Endurance index (secs) [immediately, 5 and 10 min post Rx]	2 INCREASED[a]	2. still increased from baseline at 5 and 10 mins
Kubo [30] [RCO]	N=8 healthy males Mean age: 26 (± 2yrs)	- CWI at 5°C, 30 min (lower limb immersion up to head of fibula) -HWI at 42°C, 30 min (lower limb immersion up to head of fibula)	Not assessed	ANKLE P/F ISOMETRIC DYNAMOMETER 1. Peak force: (Nm) [immediately post Rx]	1 DECREASED[a]	N/A
Richendollar [31] [RCO]	N=24 healthy males Mean age: 21.3 (± 3.3 yrs)	-Rest only, 20 minute -Warm up only, 20 minute -Ice 20 min followed by rest 20 min -Ice 20 min followed by warm up 20 mins (Ice= 1.4 kg of crushed ice in plastic bag, secured with compression wrap over anterior thigh)	Not assessed	LOWER LIMB 1. Single leg vertical jump (cm) 2. Shuttle run agility (time to complete, sec) 3. 40 yard sprint (time to complete, secs) [20 minutes post Rx]	N/A	1, 2 and 3 WORSE[b] (20 minute ice followed by 20 minutes rest vs 20 minute rest only) There were no significant findings when 20 minutes ice was followed by a 20 minute warm up
Wassinger [32] [Observational]	N=22 healthy 14 male, 8 female Mean age: 21.6 (± 2.4 yrs)	-Ice cubes, 20 mins (secured with standardised elastic bandage to centre of bag over the tip of Acromion)	Not assessed	UPPER LIMB 1. Throwing accuracy (number of throws to hit a target and number of throws in 30 secs) [immediately post Rx]	1 DECREASED[a]	N/A

Patterson [33] [Observational]	N=21 healthy 7 male, 13 female Mean age 19.8 (± 1.2 yrs)	-CWI at 10°C, 20 mins (lower leg immersion with water turbulence)	Not assessed	LOWER LIMB 1. Counter movement jump [Peak power and Average power (Watts)] 2. T-test agility (time to complete, secs) 3. 40 yard sprint (time to complete, secs) [immediately and at 5 minute intervals up to 30 minutes]	1 DECREASED[a],2 and 3 INCREASED[a]	1 WORSE at 30 mins post Rx[a] 2 WORSE for up to 5 mins post Rx[a] 3 WORSE for up to 20 mins post Rx[a]
Fischer [34] [Cross over]	N=42 healthy 25 female, Mean age 22 (± 0.5yrs) 17 male, Mean age 23 (± 0.5yrs)	- Cubed ice, 3 min (hamstring muscle belly, secured with plastic wrap) -Cubed ice, 10 min (hamstring muscle belly, secured with plastic wrap) -Rest	Not assessed	LOWER LIMB 1. Co-contraction (agility test, sec) 2. Shuttle run (time to complete, sec) 3. Single leg vertical jump (cm) [immediately, 20 mins post Rx]	2 INCREASED[a] and 3 DECREASED[a] after 10 minutes of ice No significant findings reported after 3 minute ice	2 WORSE at 20 mins post Rx[a]
Chen [35] [Observational]	N=24 healthy 12 male, 12 female Mean age: ~25 yrs	-CWI in 11°C, 40 minutes (immersion of hand and forearm)	Skin temperature 12.5°C	UPPER LIMB 1.Gross dexterity 2. Fine dexterity 3. Grip strength, gauge with load cell (kg/w) [1 and 2: after 2, 10, 18, 26, 34 and 40 minutes of CWI. Outcome 3 recorded after 40 minutes of CWI only] [immediately post Rx]	1,2 and 3 all DECREASED[a]	N/A
Dewhurst [36] [RCO]	N=27 healthy females Young subgroup (n=15): mean age 21.5 (± 2.2 yrs) Old subgroup (n=12): mean age: 73.6 (± 3.2 yrs)	-Cold, 30°C I/M temperature -Control, 34°C I/M temperature -Warm, 38°C I/M temperature All: quad, 1 cm below subcutaneous fat; ice and hot packs used to regulate temperature	I/M temperature: 30°C	KNEE EXT ISOKINETIC DYNAMOMETER 1. ISOMETRIC peak torque 2. CONC peak torque ((Velocities of 30, 60, 90 and 120°.sec^{-}) [immediately post Rx]	2 DECREASED[b] (vs control) note: in young sub-group only	N/A
Dixon [37] [RCO]	N = 9 male athletes Mean age 22.1 (± 1.5yrs)	- CWI at 12°C, 45 mins followed by no warm up - CWI 12°C, 45 mins followed by warm up - Standing control, 45 mins followed no warm up - Standing control, 45 mins followed by warm up (bilateral immersion of lower limbs up to the gluteal fold)	Not assessed	LOWER LIMB 1.Counter movement jump (Power output: Watts) [immediate, 15 minutes post Rx]	1 DECREASED[b] (after both CWI protocols compared to both ambient temperature protocols).	In group using CWI without active warm, 1 remained WORSE at 15 mins post Rx[ab] (versus all groups)

Pereir [38] [RCT]	N=18 healthy 11 male, 7 female Mena age: 22 (SE 1yr)	-Crushed ice pack, 30 mins (antero-lateral surface of lower limb, secured with elastic wrap) -Rest, 30 mins	Skin temperature 11.9 (SE 0.7°C)	ANKLE D/F ISOMETRIC STRAIN GAUGE 1.Peak force (N) [immediate, 5, 15, 30 and 60 minutes post Rx]	1 DECREASED[ab]	Immediate only

[a]: $p<0.05$ vs pre-treatment

[b]: $p<0.05$ vs control group

RCO = randomised cross over trial; RCT = randomised controlled trial; CWI = cold water immersion; HWI = hot water immersion; I/M = intra-muscular; ROM = range of movement; ECC = eccentric; CONC = concentric; PF = plantar flexion; D/F = dorsiflextion; EXT = extension; INV = inversion; ABD = abduction; MVC = maximum voluntary contraction; Rx = treatment; N/A = follow ups not measured beyond the immediate stages post Rx.

Figure I

Summary of search strategy and selection process based on included and excluded studies (QUORUM).

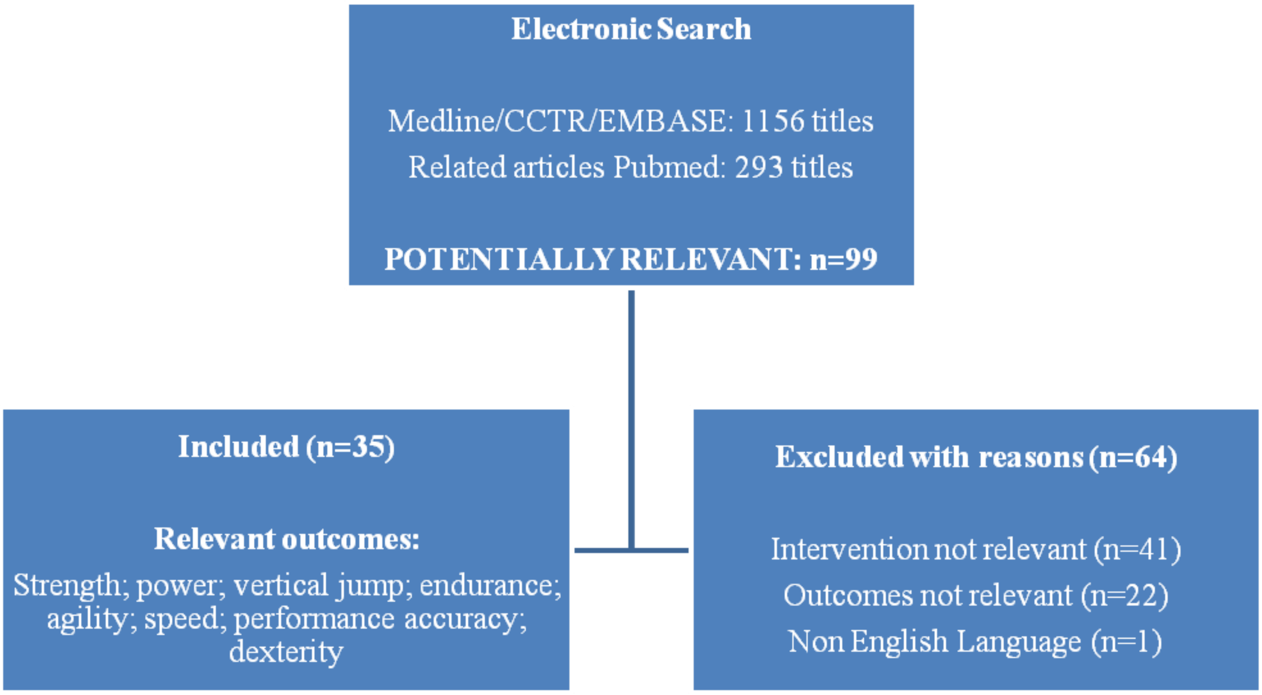


Figure II

Risk of bias summary

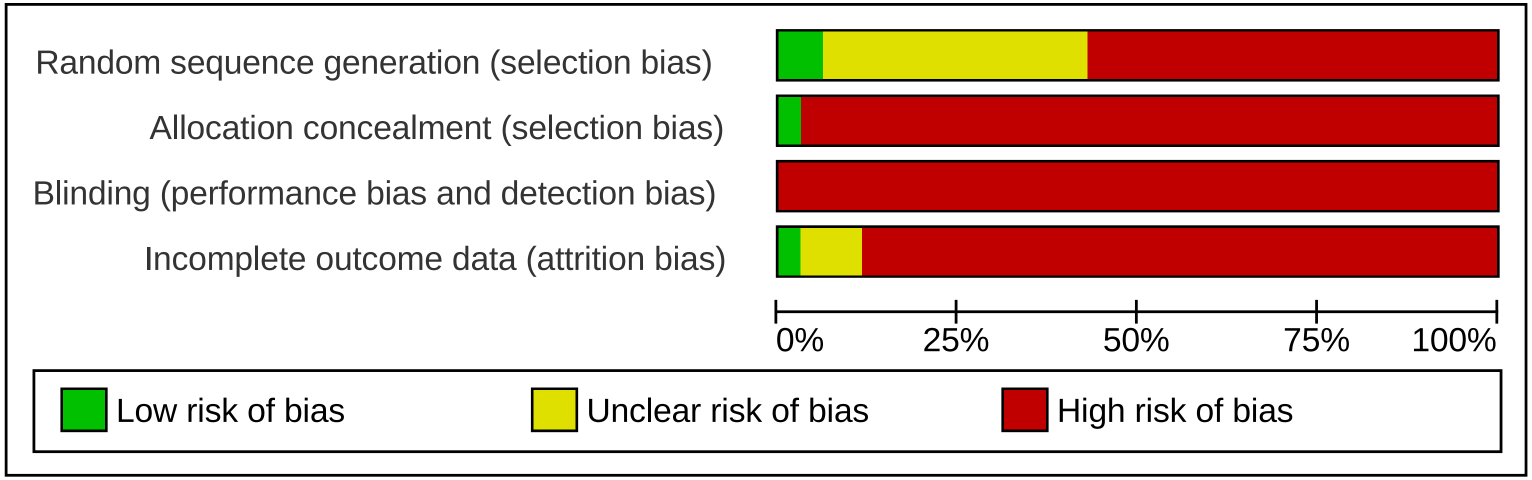
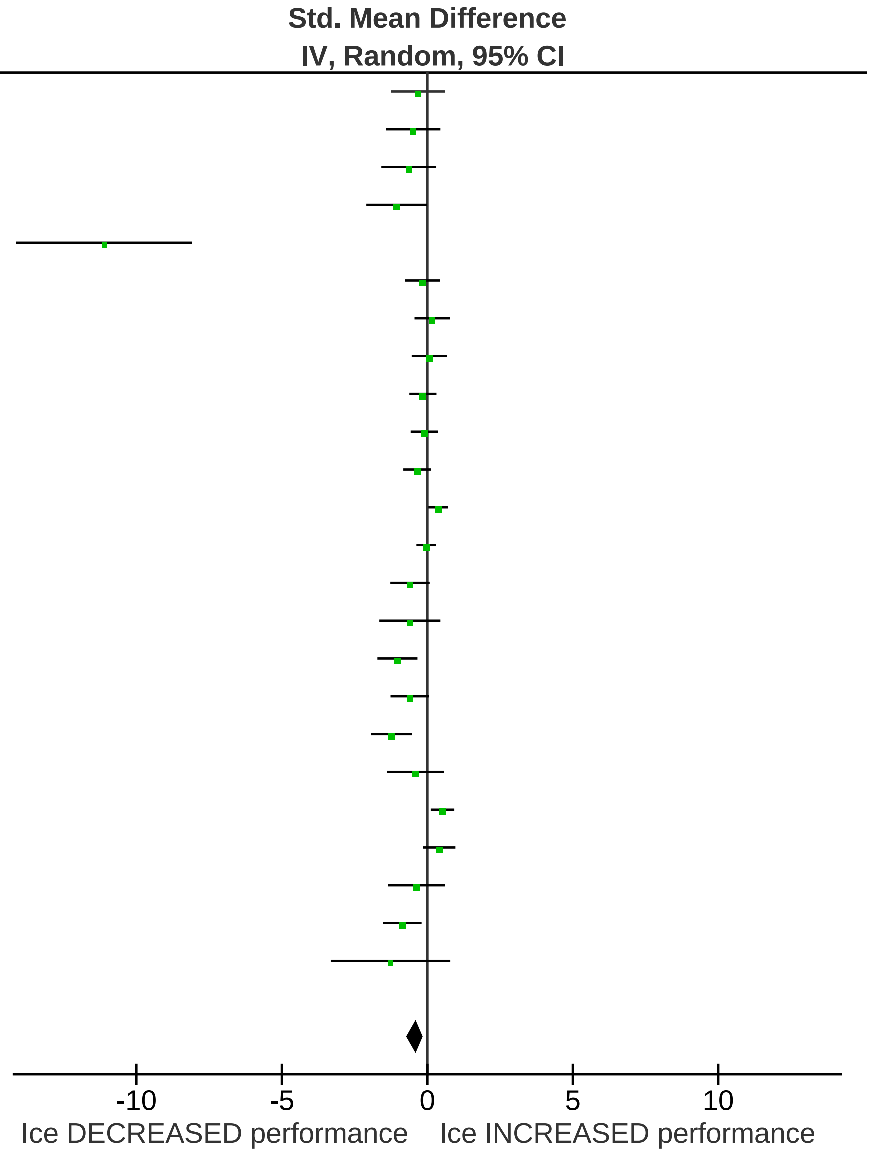


Figure III

Forest plot summarising the immediate effect (SMD 95% CI) of cooling on functional performance (within groups versus baseline)

Study or Subgroup	Std. Mean Difference IV, Random, 95% CI
Cross 1996	-0.32 [-1.20, 0.57]
Cross 1996	-0.49 [-1.38, 0.41]
Cross 1996	-0.64 [-1.54, 0.27]
Dixon 2010	-1.06 [-2.06, -0.05]
Douris 2003	-11.11 [-14.10, -8.12]
Evans 1995	-0.17 [-0.73, 0.40]
Evans 1995	0.17 [-0.40, 0.73]
Evans 1995	0.07 [-0.50, 0.64]
Fischer 2009	-0.15 [-0.58, 0.28]
Fischer 2009	-0.11 [-0.53, 0.32]
Fischer 2009	-0.35 [-0.79, 0.08]
Hamzat 2005	0.37 [0.08, 0.67]
Hamzat 2005	-0.04 [-0.33, 0.25]
Hatzel 2000	-0.60 [-1.23, 0.04]
Kubo 2005	-0.60 [-1.61, 0.41]
Patterson 2008	-1.03 [-1.68, -0.38]
Patterson 2008	-0.60 [-1.22, 0.02]
Patterson 2008	-1.24 [-1.90, -0.57]
Pereira 2010	-0.41 [-1.34, 0.53]
Sanya 1999	0.52 [0.16, 0.89]
Sanya 1999	0.41 [-0.10, 0.92]
Thornley 2003	-0.37 [-1.31, 0.56]
Wassinger 2007	-0.86 [-1.48, -0.24]
Zhou 1998	-1.27 [-3.28, 0.75]
Total (95% CI)	**-0.39 [-0.66, -0.11]**

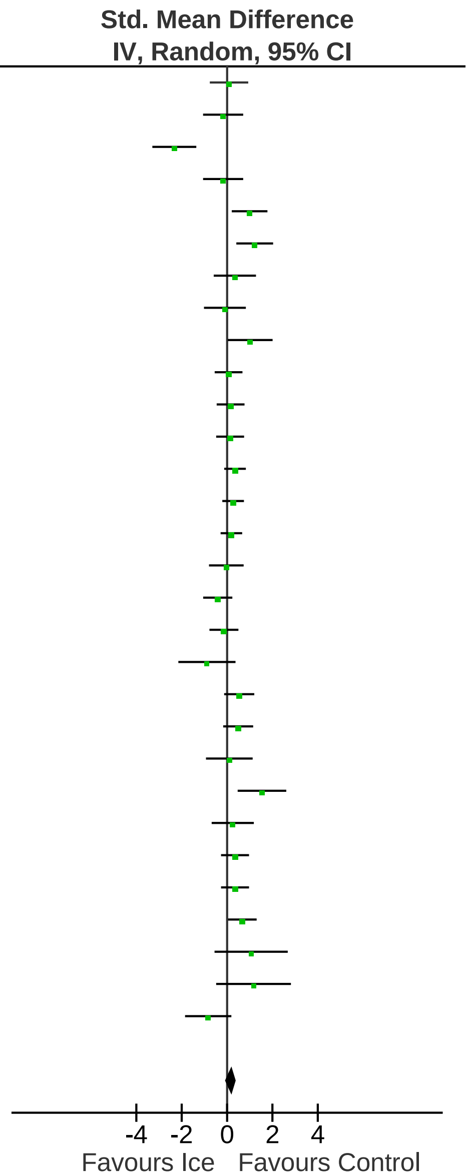


Heterogeneity: Tau² = 0.33; Chi² = 118.00, df = 23 (P < 0.00001); I² = 81%
Test for overall effect: Z = 2.78 (P = 0.005)

Figure IV

Forest plot summarising the immediate effect (SMD 95% CI) of cooling on functional performance (Ice versus control)

Study or Subgroup	Std. Mean Difference IV, Random, 95% CI
Barter 1984	0.09 [-0.71, 0.89]
Borgmeyer 2004	-0.17 [-1.01, 0.66]
Catlaw 1996	-2.33 [-3.25, -1.40]
Catlaw 1996	-0.17 [-1.01, 0.66]
Cheung 2003	1.00 [0.25, 1.74]
Cheung 2003	1.22 [0.46, 1.98]
Cross 1996	0.34 [-0.54, 1.23]
Cross 1996	-0.09 [-0.97, 0.78]
Cross 1996	1.02 [0.07, 1.96]
Evans 1995	0.07 [-0.50, 0.63]
Evans 1995	0.16 [-0.41, 0.72]
Evans 1995	0.14 [-0.43, 0.70]
Fischer 2009	0.35 [-0.08, 0.78]
Fischer 2009	0.27 [-0.16, 0.70]
Fischer 2009	0.19 [-0.24, 0.62]
Hopkins 2002a	-0.03 [-0.75, 0.68]
Kimura 1997	-0.41 [-1.01, 0.19]
Kimura 1997	-0.14 [-0.73, 0.45]
Lackie 1995	-0.89 [-2.10, 0.32]
Matacola 1993	0.53 [-0.08, 1.15]
Matacola 1993	0.49 [-0.12, 1.11]
Pereira 2010	0.10 [-0.88, 1.08]
Petrofsky 1980	1.54 [0.51, 2.56]
Petrofsky 1980	0.25 [-0.63, 1.13]
Richendollar 2006	0.35 [-0.22, 0.92]
Richendollar 2006	0.35 [-0.22, 0.92]
Richendollar 2006	0.67 [0.09, 1.25]
Sargeant 1987	1.06 [-0.51, 2.63]
Sargeant 1987	1.17 [-0.43, 2.77]
Thornley 2003	-0.83 [-1.80, 0.14]
Total (95% CI)	**0.20 [-0.00, 0.41]**



Heterogeneity: $Tau^2 = 0.18$; $Chi^2 = 73.21$, df = 29 ($P < 0.0001$); $I^2 = 60\%$
Test for overall effect: Z = 1.91 (P = 0.06)