

Cooling and Performance Recovery of Trained Athletes: A Meta-Analytical Review

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Purpose: Cooling after exercise has been investigated as a method to improve recovery during intensive training or competition periods. As many studies have included untrained subjects, the transfer of those results to trained athletes is questionable. **Methods:** Therefore, the authors conducted a literature search and located 21 peer-reviewed randomized controlled trials addressing the effects of cooling on performance recovery in trained athletes. **Results:** For all studies, the effect of cooling on performance was determined and effect sizes (Hedges' g) were calculated. Regarding performance measurement, the largest average effect size was found for sprint performance (2.6%, $g = 0.69$), while for endurance parameters (2.6%, $g = 0.19$), jump (3.0%, $g = 0.15$), and strength (1.8%, $g = 0.10$), effect sizes were smaller. The effects were most pronounced when performance was evaluated 96 h after exercise (4.3%, $g = 1.03$). Regarding the exercise used to induce fatigue, effects after endurance training (2.4%, $g = 0.35$) were larger than after strength-based exercise (2.4%, $g = 0.11$). Cold-water immersion (2.9%, $g = 0.34$) and cryogenic chambers (3.8%, $g = 0.25$) seem to be more beneficial with respect to performance than cooling packs (-1.4%, $g = -0.07$). For cold-water application, whole-body immersion (5.1%, $g = 0.62$) was significantly more effective than immersing only the legs or arms (1.1%, $g = 0.10$). **Conclusions:** In summary, the average effects of cooling on recovery of trained athletes were rather small (2.4%, $g = 0.28$). However, under appropriate conditions (whole-body cooling, recovery from sprint exercise), postexercise cooling seems to have positive effects that are large enough to be relevant for competitive athletes.

Keywords: cryotherapy, cold-water immersion, regeneration

For athletes in many kinds of sports, maintenance of performance over longer periods despite high physical stress is considerably important.¹ This refers to both intensive training periods and strenuous competition phases that can last up to several weeks (eg, tournaments in team sports, stage races in cycling, world championships in rowing).

For this reason, there is an increased interest in methods to support fast recovery between intensive exposure periods. One of the methods that recently have come into the focus of research is postexercise application of cold.¹⁻⁴ Several possible beneficial mechanisms of cooling have been suggested,³ including muscle temperature decrease, reducing muscle damage, as well as postexercise inflammation⁵; reduced heart rate and cardiac output⁶; peripheral vasoconstriction; reduced peripheral edema formation^{5,7}; and analgesic effects.⁸ However, with respect to recovery from exercise, the actual physiological mechanisms underlying potential benefits of cooling interventions are still unclear.^{4,9}

Different methods have been proposed for cooling in sports, including cold-water application, cooling vests or packs, cooled rooms or cryogenic chambers, ice massage,

and cold drinks.¹⁰ These methods are used for different applications that, apart from recovery intervention, include precooling^{10,11} and cryotherapy after injury,¹² with cold-water immersion (CWI) being the most commonly used method.²

Recently, 2 review articles on the effects of postexercise cooling have been published.^{1,2} Halson² investigated the influence of the time frame on the effectiveness of hydrotherapy (cold application and/or contrast water therapy) for recovery and found that the effects of cooling on recovery were larger for weight-bearing sports (running, weight training, eccentric exercise) than for non-weight-bearing sports (cycling, swimming). The author pointed out that for CWI no gold standard regarding water temperature, immersion depth, and duration has been established yet but provides educated suggestions based on the available literature (whole-body immersion lasting 10–20 min at a water temperature of 10–15°C). Training status of the participants in the included studies ranged from untrained subjects to elite athletes. For future studies, Halson² recommended investigating the highest level of athlete possible, as untrained subjects and elite athletes may differ with respect to their responsiveness to recovery strategies.

Leeder et al¹ evaluated 14 studies examining the effects of CWI on recovery from eccentric and high-intensity exercise. The review included studies with

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both trained athletes and untrained or recreational subjects. The authors focused on 4 key outcome variables: muscle power, muscle strength, delayed-onset muscle soreness, and creatine kinase concentration. They found that although CWI was an effective strategy to reduce delayed-onset muscle soreness, the effects on performance were less clear. While CWI did not improve recovery of muscle strength (isometric–isokinetic extension–flexion), positive effects were found for muscle power (jump and sprint performance). The authors emphasized the importance of research on the influence of different parameters (eg, cooling method, cooling duration, type of performed exercise) on performance recovery. Due to the limited amount of available studies, it was not possible for Leeder et al to statistically evaluate the influence of various study-design parameters (eg, cooling method and duration, type of exercise performed) on different performance components.¹

Several studies have included untrained subjects or recreational athletes not participating in competitive sports.^{7,13,14} In some of those, the presence of a training history was explicitly mentioned as an exclusion criterion.^{13,14} While the use of untrained subjects has some advantages (eg, better availability, potentially larger degree of fatigue and soreness due to reduced fitness level making it easier to observe intervention effects^{15,16}), interpretation and transfer of the results in the context of elite athletes is difficult.^{2,17,18} To date, no review has focused on the effects of postexercise cooling on performance recovery of trained athletes.

Since 2011, a large number of studies on cooling for performance recovery have been published, providing a significantly increased body of data. These new insights have opened up the possibility to statistically evaluate the effects of cooling on recovery, taking into account specific parameters of the study design. The current review aimed to analyze the current literature on cold application for recovery with special reference to its effect on performance in trained athletes. To this end, the studies to date were evaluated with respect to the methodology of cooling (eg, duration, temperature, and type of cold application) and the exercise protocols used to both induce exhaustion and measure the influence of cooling on performance recovery. Particular attention was paid to the application of cold during the recovery process in high-level sports.

Methods

A literature search was carried out by 2 independent researchers for articles published through December 2012, using different sets of 10 keywords (*recovery, regeneration, cooling, intervention, exercise, performance, effects, cold-water immersion, ice water, and delayed-onset muscle soreness*) combined by Boolean logic (AND). The following databases were searched: PubMed, ISI Web of Science, the Allied and Comple-

mentary Medicine Database (AMED), the Cochrane Database of Systematic Reviews, and the Excerpta Medica Database (EMBASE). Moreover, citation tracking of key primary and review articles was undertaken to obtain further articles.

Selection Criteria

Only studies from peer-reviewed journals were considered. The obtained articles were evaluated with respect to their suitability and significance for the desired context. A study was only included if it fulfilled the following criteria:

- To draw conclusions relevant for competitive sports, studies were included only if it was clearly stated that the subjects were trained athletes—competitive at least on regional level, active at least 3 times per week, or maximum oxygen uptake at least 55 ml/kg/min¹⁰ (dropouts: 13).
- The study had to include an experimental condition with a cooling intervention taking place after exercise. Studies using combined interventions (eg, cooling and active recovery) instead of pure cooling were excluded (dropouts: 24).
- The gold standard to assess the state of postexercise fatigue and recovery is the measurement of performance parameters.¹⁹ For this reason, the state of recovery had to be plausibly measured using at least 2 identical performance tests (one before exercise and the other or others after the recovery period). The exercise itself was accepted to act as the first performance test. Studies that only evaluated the effects of cooling on physiological markers (eg, blood parameters) were excluded (dropouts: 11).
- It included a control condition with a passive recovery protocol, with the subjects either acting as their own control (randomized crossover design) or being randomly divided into an intervention group and a control group (dropouts: 11).
- To exclude a potential precooling effect on posttest performance (ie, an acute effect on performance due to the reduction of body temperature^{10,11}), only studies with a time period of more than 90 minutes between cooling intervention and posttest were included. For intervals of 90 minutes and more between cooling and posttest, precooling effects are unlikely¹⁰ (dropouts: 7).

Classification of the Studies

For further analysis, the selected studies were classified into different groups according to the following criteria:

- Depending on the type of performance investigated in the pretest and posttest, studies were grouped into 4 different performance components: endurance,

strength, sprint, and jump. Endurance performance included time trials or covered distances during simulated team games, while strength performance was related to isometric muscle performance (eg, maximum voluntary contraction). Single or repeated sprints were classified as sprint performance, and jump performance was usually tested with counter-movement jumps.

- Further groups were formed with respect to the method used for cooling. Three cooling methods were identified: CWI, cryogenic chambers (-110°C), and cooling packs. For CWI, 2 subgroups were formed: whole-body CWI (at least up to the sternum) and partial-body CWI (arm or leg cooling).
- Another classification criterion was the time between exercise and the posttest to evaluate performance.
- The studies were also grouped according to the type of exercise used to induce fatigue (endurance training and strength training). While endurance training included running, cycling, (simulated) team matches, or intermittent sprint exercise, strength training was usually eccentric weight training.

In many studies, several performance components were analyzed, or several posttests were performed at different points of time. In those cases, the respective results were considered separately; that is, studies may appear in several groups.

Data Extraction and Treatment

A standardized form was used to extract relevant data and key methodological details from the studies. For each study, the relative change in performance (pretest vs posttest) for the cooling and the control condition was calculated. By subtracting the 2 values, the net effect of cooling on performance recovery was calculated.

Effect sizes (Hedges' g) and 95% confidence intervals were calculated according to

$$g = c_p \left[\frac{(M_{\text{post,cooling}} - M_{\text{pre,cooling}}) - (M_{\text{post,control}} - M_{\text{pre,control}})}{SD_{\text{pre}}} \right]$$

with $M_{\text{pre,cooling}}$, $M_{\text{post,cooling}}$, $M_{\text{pre,control}}$, and $M_{\text{post,control}}$ being the respective mean values of performance (pretest, posttest; cooling, control), SD_{pre} the pooled pretest standard deviation, and c_p the bias factor to adjust for small sample size.²⁰ This method was chosen as it was recommended for effect-size calculation of controlled pretest–posttest–design studies in meta-analyses based on simulation results showing its superior properties with respect to bias, precision, and robustness to heterogeneity of variance compared with other methods.²⁰ Negative effects (performance impairments due to cooling) were denoted with a minus sign. When studies reported only standard errors, standard deviations were calculated by multiplying standard errors by the square root of the

sample size. Overall outcome for the analyzed conditions was assessed by calculating n -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 scale²¹: $<.20$ = negligible effect, $.20$ – $.49$ = small effect, $.50$ – $.79$ = moderate effect, $\geq.80$ = large effect.

Results

Twenty-one studies with a total number of 216 subjects met all selection criteria and were considered for evaluation (Figure 1 and Table 1). Weighted average increase of performance was 2.4%, and the weighted average effect size was $g = 0.28$.

For further evaluation, these studies were analyzed with respect to the performance component used for recovery evaluation: endurance (5 studies), strength (10 studies), sprint (11 studies), and jump (9 studies). Moreover, the timing of postcooling performance testing was considered: 2 to 3 hours (4 studies), 24 hours (17 studies), 48 hours (12 studies), 72 hours (7 studies), 96 hours (3 studies), 120 hours (1 study), and 144 hours (2 studies) after exercise. In 5 studies, an eccentric strength-training protocol was applied to induce fatigue, while 16 studies used an endurance-type exercise protocol including intermittent sprints. Of the latter, in 11 studies a single-bout exercise was applied, and 5 studies used a repeated-exercise protocol (over a period of 3–6 d).

In 16 studies, CWI was used to cool the subjects (leg immersion, 10 studies; arm immersion, 1 study; whole-body immersion at least up to the sternum, 5 studies). Of those, 8 studies used a continuous cooling protocol (5–15 min), and in 8 studies intermittent CWI was performed (2×5 min, 2×9 min, 5×1 min, 5×2 min, or 5×20 min). Water temperature was 5 – 15°C (average $11.1^{\circ}\text{C} \pm 2.8^{\circ}\text{C}$).

Cryogenic chambers were used in 2 studies (two and three 3-min stays at -110°C , separated by 2 h and 24 h, respectively), and cooling packs or vests were used in 3 studies (20 min or 5×15 min).

In 15 studies, a randomized crossover design was used with the participants acting as their own controls, enabling a comparison on an intraindividual basis. The remaining 6 studies were randomized controlled trials where the subjects were divided into several groups. In 8 studies, the exercise to provoke exhaustion was directly used to determine performance and was thus repeated for the posttest. The other 13 studies used a separate protocol for performance evaluation.

Effect of Cooling on Different Performance Components

The forest plots for the different performance components are displayed in Figures 2–5. The results from the individual groups were sorted with respect to the period between the exercise to induce fatigue and the performance test (2–144 h).

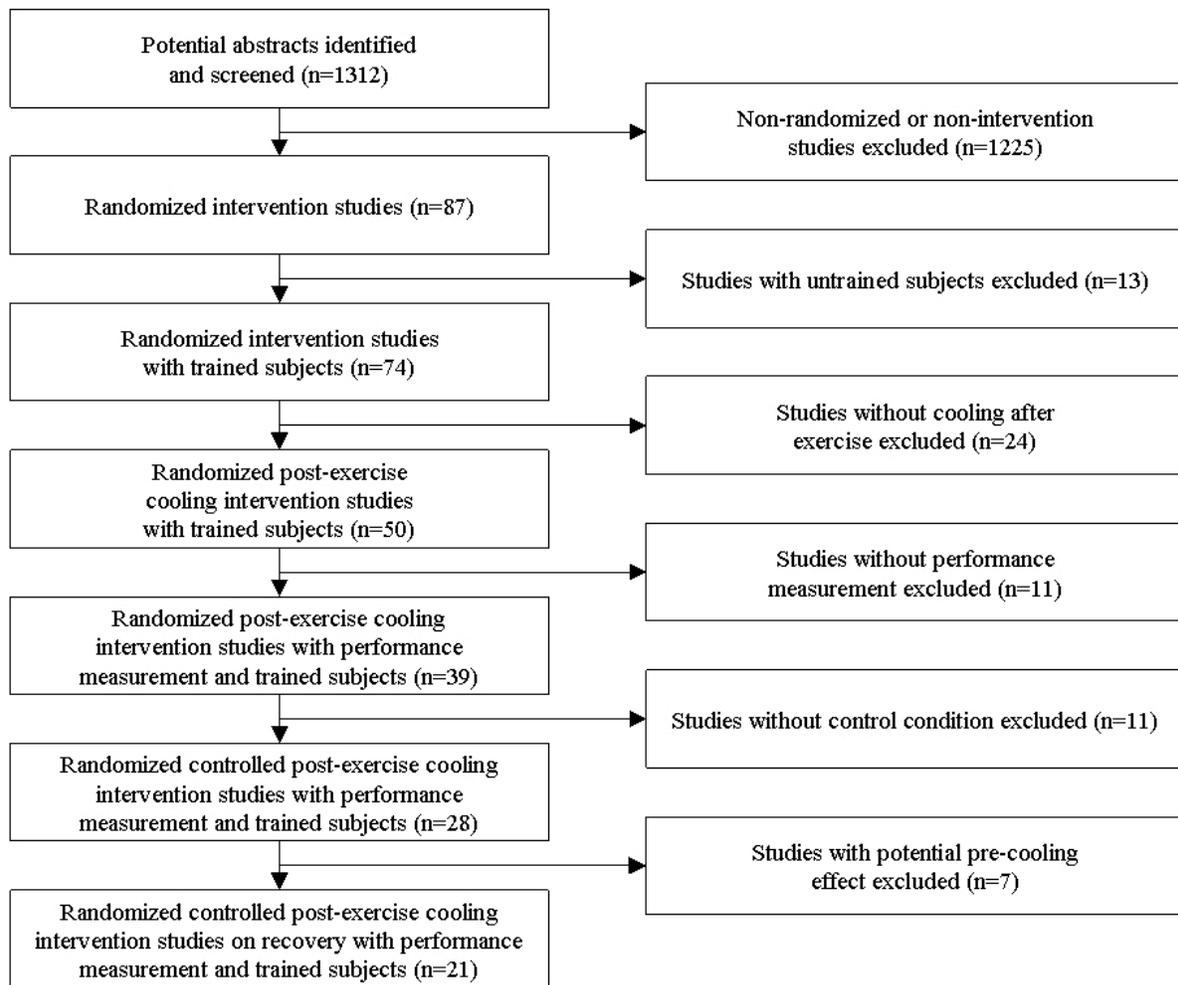


Figure 1 — Flowchart of the study selection process.

On average, the best results were found for sprint recovery (+2.6%, Figure 4). For the other investigated performance components, average effect sizes were considerably smaller, although relative improvement of performance was in a similar range for endurance recovery (+2.6%, Figure 2) and jump recovery (+3.0%, Figure 5). For strength recovery (+1.8%, Figure 3), both average effect size and relative improvement of performance were smaller.

Effect of Cooling Method

Most studies used CWI as the cooling method (+2.9%, $g = 0.34$ [0.22, 0.46]). Compared with cryogenic chambers (+3.8%, $g = 0.25$ [−0.17, 0.66]), average effect size was slightly higher for CWI. For cooling packs (−1.4%, $g = -0.07$ [−0.35, 0.21]), average effects were negligible.

When only the exercised limb (leg or arm) was cooled (+1.1%, $g = 0.10$ [−0.06, 0.26]) the effects were significantly smaller than with whole-body CWI (+5.1%, $g = 0.62$ [0.45, 0.80]).

To determine the optimal parameters for cooling, the CWI studies were analyzed with respect to cooling temperature. In Figure 6, cooling temperature is displayed relative to the effect sizes found for the different studies.

Effect of Time Between Pretest and Posttest

With respect to the timing of the postcooling performance test, the best average results of cooling were found 96 hours after the fatiguing exercise (+4.3%, $g = 1.03$ [0.57, 1.49]). Smaller average effects were found for performance tests 72 hours (+2.9%, $g = 0.43$ [0.17, 0.70]), 48 hours (+3.4%, $g = 0.27$ [0.06, 0.47]), and 24 hours (+2.0%, $g = 0.20$ [0.04, 0.36]) after exercise. Average effect sizes for short-term (2–3 h) recovery periods (−1.0%, $g = -0.03$ [−0.46, 0.40]), as well as for 120 hours (−1.7%, $g = -0.11$ [−1.09, 0.87]) and 144 hours (+0.2%, $g = -0.08$ [−0.77, 0.62]) between exercise and the post-cooling performance test, were negligible.

Table 1 Summary of the Studies

| Study | Subjects, N | Exercise to provoke exhaustion | Intervention | Performance measure | Effects on performance (effect size) |
|---------------------------------|---|--|--|--|--|
| Costello et al ³¹ | 9+9, ^a physically active at least 3 times per wk | Single exercise, 5 × 20 high-force maximal eccentric contractions of the left knee extensors | 2 × 3 min in cryochamber at -110°C (24 and 26 h after exercise) | Strength (MVIC) | post 48 h: -2.4% (g = -0.18) post 72 h: -1.3% (g = -0.10) post 96 h: +4.7% (g = +0.35) |
| De Nardi et al ³² | 6+6 ^a Junior Regional League soccer players | Repeated exercise over 4 d, 140 min soccer training per d | 8-min leg CWI at 15°C | Jump (CMJ) | post 24 h: -3.2% (g = -0.49) post 48 h: -0.7% (g = -0.11) post 72 h: +1.8% (g = 0.25) |
| Delextrat et al ²² | 16 University Premier League basketball players (8 men, 8 women) | Single exercise, competitive basketball match | 5 × 2-min leg CWI at 11°C (2-min break) | Sprint (12 × 20 m) Jump (CMJ) Sprint (10 × 30 m) | post 24 h: -0.5% (g = -0.13) post 48 h: ±0.0% (g = ±0.00) post 72 h: +3.8% (g = 0.82) |
| Elias et al ²³ | 8+8 ^a professional Australian Football players | Single exercise, 75-min Australian Football match | 14-min whole-body CWI at 12°C | Jump (CMJ) | post 24 h: +5.1% (g = +0.56) post 24 h: +0.5% (g = +0.13) |
| Hauswirth et al ²⁴ | 9 well-trained runners, minimum 10-km performance 38 min | Single exercise, 48-min simulated running trail (15-min downhill sections) | Repeated cooling, 3 × 3 min in cryochamber at -110°C (post-race, post 24 h, and post 48 h) | Jump (CMJ) | post 24 h: +12.4% (g = +0.68) post 48 h: +11.1% (g = +0.61) |
| Higgins et al ⁴¹ | 8+8 ^a well-trained U/20 rugby team | Repeated exercise over 6 days, 2 simulated rugby matches (separated by 144 h) with 3 training sessions between | Repeated cooling, 2 × 5-min leg CWI at 10°C (2.5-min break), applied after first game and after training | Sprint (6 × 20 m) | post 24 h: +3.7% (g = +1.54) post 48 h: +1.9% (g = +0.80) |
| Ingram et al ²⁵ | 11 team-sport athletes | Single exercise, 4 × 20 min intermittent sprint, then 20-m shuttle-run test to exhaustion | Repeated cooling, 2 × 5-min leg CWI at 10°C (2.5-min break), applied 0 and 24 h after exercise | Strength (MVIC) | post 24 h: +10.8% (g = +0.73) post 48 h: +7.4% (g = +0.44) |
| King and Duffield ³⁰ | 10 female netball players active 4–5 times per wk | Single exercise, 4 × 15 min intermittent sprint | 2 × 5-min leg CWI at 9.3°C (2.5-min break) | Sprint (20 m, 30 m) | post 144 h: -1.4% (g = -0.26) |
| Lane and Wenger ²⁶ | 10 physically active men, average VO _{2max} 55 mL/kg/min | Single exercise, 18-min intermittent cycling sprint | 15-min leg CWI at 15°C | Sprint (10 × 20 m) Strength (MVIC) Sprint (5 × 20 m) Jump (CMJ) Endurance (total work during 18 min intermittent cycling sprint) | post 48 h: +1.2% (g = +0.34) post 48 h: +3.5% (g = +0.15) post 24 h: +0.6% (g = +0.09) post 24 h: +4.3% (g = +0.27) post 24 h: +2.2% (g = +0.14) |

(continued)

Table 1 (continued)

| Study | Subjects, N | Exercise to provoke exhaustion | Intervention | Performance measure | Effects on performance (effect size) |
|--|--|---|---|--|--|
| Minnett et al ³³ | 8 members of Australian cricket state squad or professional cricketers | Single exercise, simulated cricket match | 20 min cooling with towel, cooling vest, and cooling packs | Endurance (distance over) | post 24 h: -1.2% ($g = -0.08$) |
| Montgomery et al ³⁴ | 10+9 ^a state-level basketball players training 8–10 h/wk | Repeated exercise over 3 d, 48-min basketball match per d | Repeated cooling, 5 × 1-min CWI to sternum at 11°C after each match (2-min break) | Sprint (20 m) Jump (CMJ) | post 24 h: $+4.7\%$ ($g = +0.29$) post 24 h: -5.8% ($g = -0.44$) |
| Paddon-Jones and Quigley ³⁵ | 8 weight-training-experienced subjects | Single exercise, 8 × 8 eccentric dumbbell curls (sets alternating between left and right arms) | 5 × 20-min arm CWI at 5°C (60-min break) | Sprint (20 m) Jump (CMJ) | post 72 h: $+0.6\%$ ($g = +0.16$) post 72 h: -4.4% ($g = -0.37$) |
| Pointon et al ³⁶ | 10 resistance-trained men (rugby league) training 5–6 times per wk | Single exercise, 6 × 25 maximal concentric–eccentric contractions of the dominant knee extensors | 20-min ice-cuff application on exercised leg | Strength (isometric muscle-torque moment) | post 24 h: $+5.1\%$ ($g = +0.34$) post 48 h: $+8.2\%$ ($g = +0.54$) post 72 h: -2.2% ($g = -0.14$) post 96 h: -0.8% ($g = -0.05$) post 120 h: -1.7% ($g = -0.11$) post 144 h: $+1.7\%$ ($g = +0.11$) post 2 h: $+4.0\%$ ($g = +0.19$) |
| Pointon et al ³⁷ | 10 team-sport athletes (rugby league) training 3–4 times per wk | Single exercise, 2 × 30-min intermittent sprint (10-min break) | 2 × 9-min leg CWI at 8.9°C (1-min break) | Strength (MVIC) | post 24 h: -5.9% ($g = -0.30$) post 48 h: -0.3% ($g = -0.02$) post 2 h: $+3.5\%$ ($g = +0.11$) post 24 h: -9.0% ($g = -0.36$) |
| Pointon and Duffield ⁴² | 10 team-sport athletes (rugby league) training 2–3 times per wk | Single exercise, 2 × 30-min intermittent sprint with tackling to simulate collisions (10-min break) | 2 × 9-min leg CWI at 8.9°C (1-min break) | Strength (MVIC) | post 2 h: -5.9% ($g = -0.20$) post 24 h: -1.7% ($g = -0.06$) |
| Pournot et al ³⁸ | 13+9 ^a elite team-sport athletes, average $\dot{V}O_{2\max}$ 66 mL/kg/min | Single exercise, 2 × 10 min alternating CMJ and rowing | 15-min leg CWI at 10°C | Sprint (30 s rowing) Strength (MVIC) | post 24 h: -0.8% ($g = -0.03$) post 24 h: $+8.8\%$ ($g = +0.34$) |
| Rupp et al ²⁷ | 12+10 ^a Division I college soccer players (13 men, 9 women) | Single exercise, Yo-Yo Intermittent Recovery Test | Repeated cooling, 15-min leg CWI at 12°C, applied 0 and 24 h after exercise | Jump (CMJ) Jump (CMJ) | post 24 h: $\pm 0.0\%$ ($g = +0.02$) post 24 h: $+0.6\%$ ($g = +0.03$) post 48 h: $+1.6\%$ ($g = +0.09$) post 48 h: $+2.3\%$ ($g = +0.13$) |
| | | | | Endurance (Yo-Yo Intermittent Recovery Test) | |

| | | | | | |
|-----------------------------|---|---|---|---|---|
| Stanley et al ³⁹ | 11 trained cyclists, average $\text{VO}_{2\text{max}}$ 65 mL/kg/min | Repeated exercise over 3 d, 120 min cycling (combined intermittent sprint and time trial) per d | Repeated cooling, 5-min whole-body CWI at 10.1°C, applied after each exercise session | Sprint (5–15 s cycling) Endurance (9-min cycling time trial) Isometric strength | post 24 h: +7.8% ($g = +0.57$) post 48 h: +5.9% ($g = +0.43$) post 24 h: +1.8% ($g = +0.12$) post 48 h: -0.3% ($g = -0.02$) post 3 h: -5.2% ($g = -0.21$) post 24 h: +1.7% ($g = +0.06$) post 48 h: -6.7% ($g = -0.26$) post 72 h: +1.4% ($g = +0.05$) |
| Tseng et al ⁴⁰ | 11 National University Baseball League players | Single exercise, 6 × 5 eccentric contractions of elbow flexors at 85% of 1RM | Repeated cooling, 15-min cooling packs on arms, applied 0, 3, 24, 48, and 72 h after exercise | Sprint (5–15 s cycling) | post 24 h: +2.6% ($g = +1.01$) post 48 h: +2.1% ($g = +0.75$) post 72 h: +6.7% ($g = +2.48$) post 96 h: +6.2% ($g = +2.85$) |
| Vaile et al ²⁸ | 12 male cyclists, average $\text{VO}_{2\text{max}}$ 69 mL/kg/min | Repeated exercise over 5 d, 105 min cycling (combined intermittent sprint and time trial) per day | Repeated cooling, 14-min whole-body CWI at 15°C, applied after each exercise session | Endurance (9-min cycling time trial) | post 24 h: +1.3% ($g = +0.10$) post 48 h: +3.8% ($g = +0.29$) post 72 h: +6.3% ($g = +0.48$) post 96 h: +5.6% ($g = +0.43$) |
| Vaile et al ²⁹ | 12 strength-trained men | Single exercise, 5 × 10 eccentric leg-press repetitions at 100–120% of concentric 1RM | 14-min whole-body CWI at 15°C | Strength (isometric squat) Jump (squat jump) | post 24 h: +3.2% ($g = +0.13$) post 48 h: +13.8% ($g = +0.61$) post 72 h: +9.3% ($g = +0.41$) post 24 h: +4.0% ($g = +0.17$) post 48 h: +10.6% ($g = +0.45$) post 72 h: +5.6% ($g = +0.24$) |

Note: Positive signs always indicate an improvement in performance. Abbreviations: MVIC indicates maximum voluntary isometric contraction; CWI, cold-water immersion; CMI, countermovement jump; 1RM, 1-repetition maximum.

^aNo-cross-over study (first number: subjects in cooling group, second number: subjects in control group).

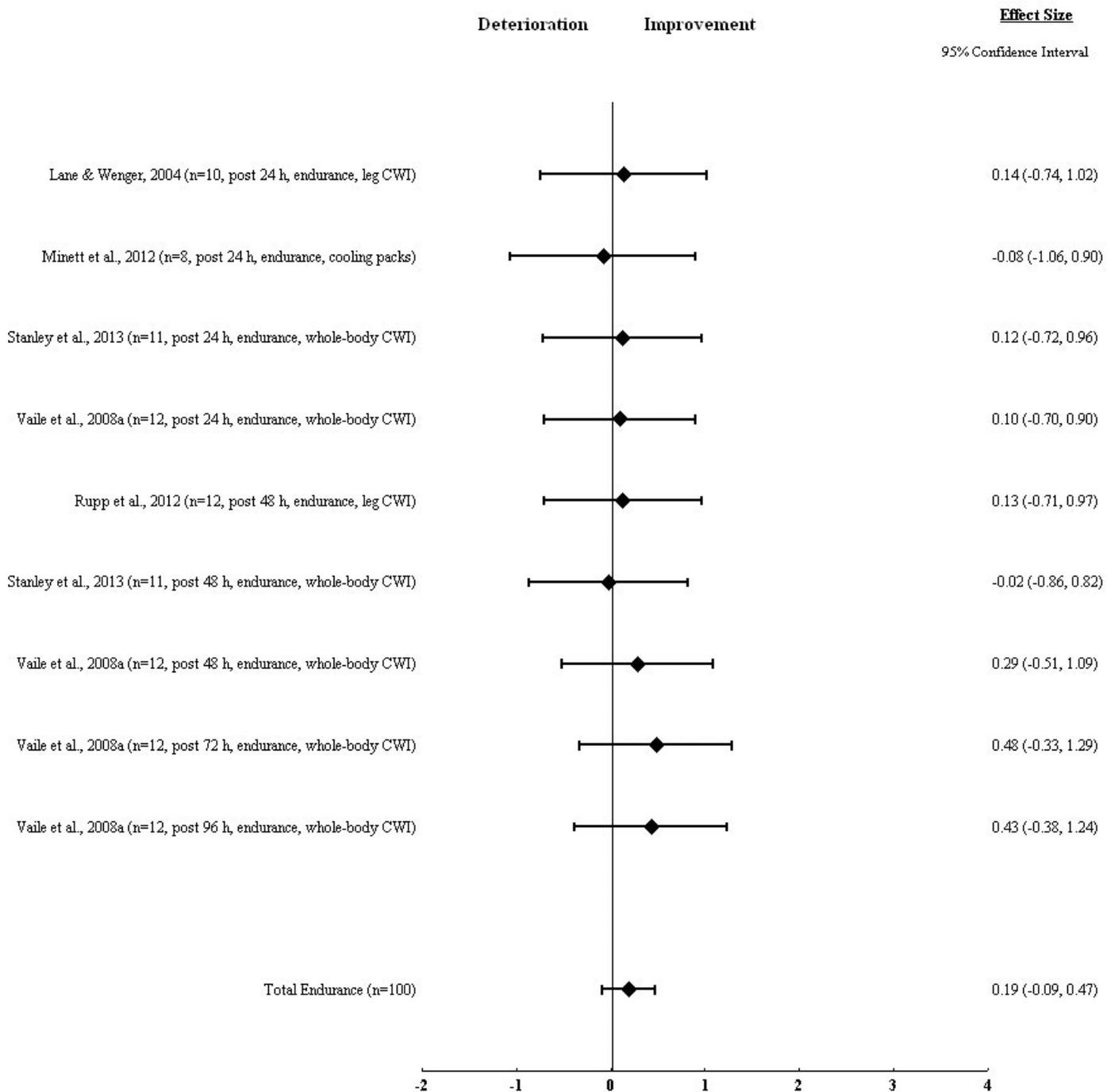


Figure 2 — Effects of cooling after exercise on recovery of endurance performance. For each study, the number of subjects (n) and the timing of the posttest (multiple timings possible) are given, as well as the type of exercise to induce fatigue and the cooling method. CWI indicates cold-water immersion.

Effect of the Fatigue Protocol

The investigated studies were divided into 2 categories according to the type of exercise protocol used to induce fatigue. Although percentage improvements were similar, effect sizes for endurance exercise (+2.4%, $g = 0.35$ [0.23, 0.48]) were larger than for eccentric strength training (+2.4%, $g = 0.11$ [-0.07, 0.30]).

Discussion

Of the 21 studies that met all selection criteria, 9 showed only positive average effects of cooling on the recovery of performance.^{22–30} In 10 studies, mixed (positive and negative) effects on different target parameters were found.^{31–40} In 2 studies, only negative average effects were observed.^{41,42} Seven of the 21 studies^{25,26,28–30,34,35} were already included

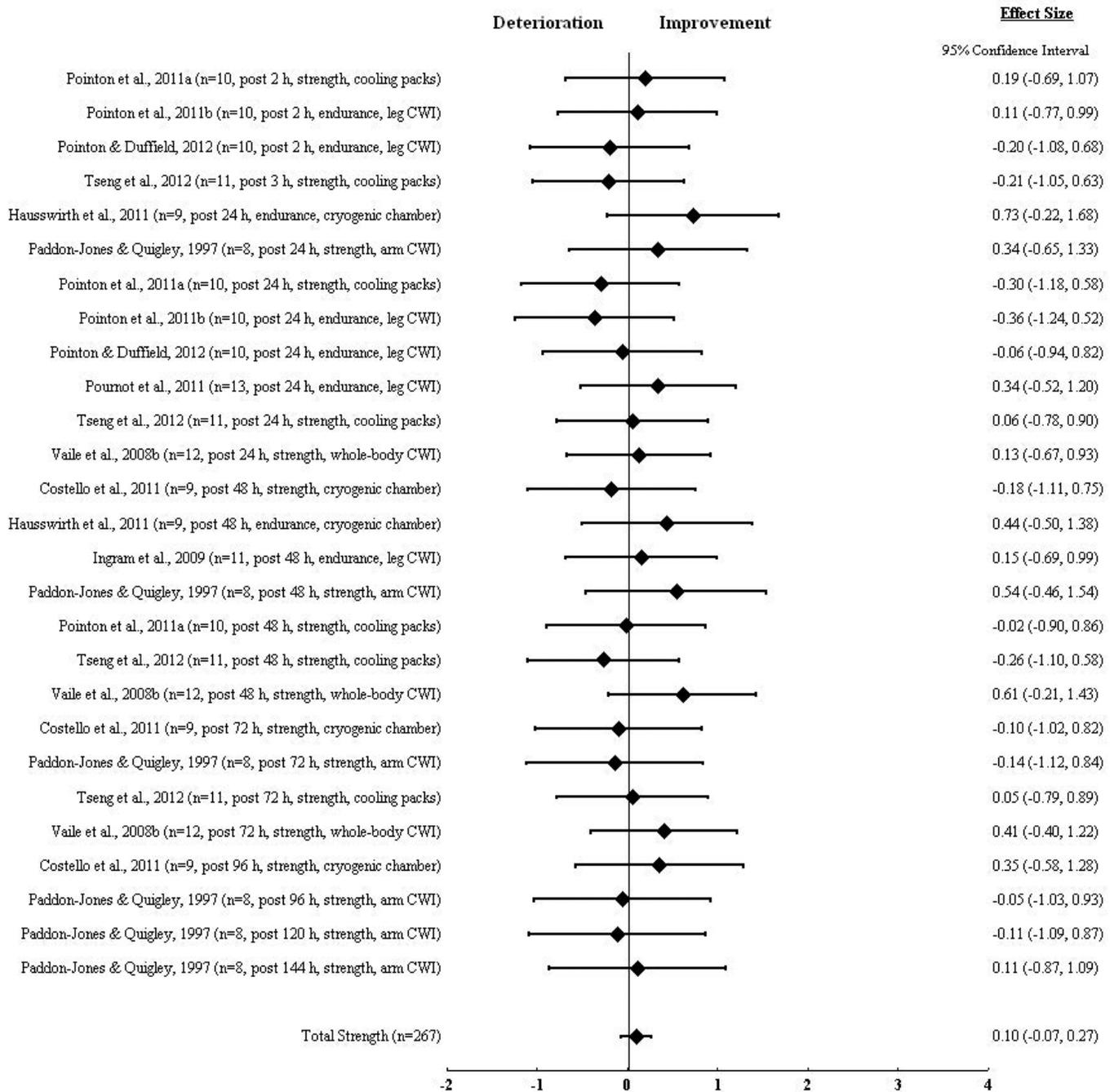


Figure 3 — Effects of cooling after exercise on recovery of strength performance. For each study, the number of subjects (*n*) and the timing of the posttest (multiple timings possible) are given, as well as the type of exercise to induce fatigue and the cooling method. CWI indicates cold-water immersion.

in at least one of the recent reviews.^{1,2} The other 14 studies have not been included in any other review to date. All those studies were published during the preceding 2 years, showing the relevance and current scientific interest in this topic.

Performance Effects

Average percentage improvements in performance for the different performance components were in the range

of 2% to 3%. According to Hopkins et al,⁴³ the minimum improvement making a certain strategy worthwhile is the value that increases the chance of victory for an athlete by 10%. For this “smallest worthwhile enhancement,” they found values of ~1% for half-marathon and marathon, and ~0.5% for shorter endurance distances and sprints.^{43,44} Therefore, for all performance components, average percentage improvements were in a range relevant for competitive sports. However, similar to Leeder

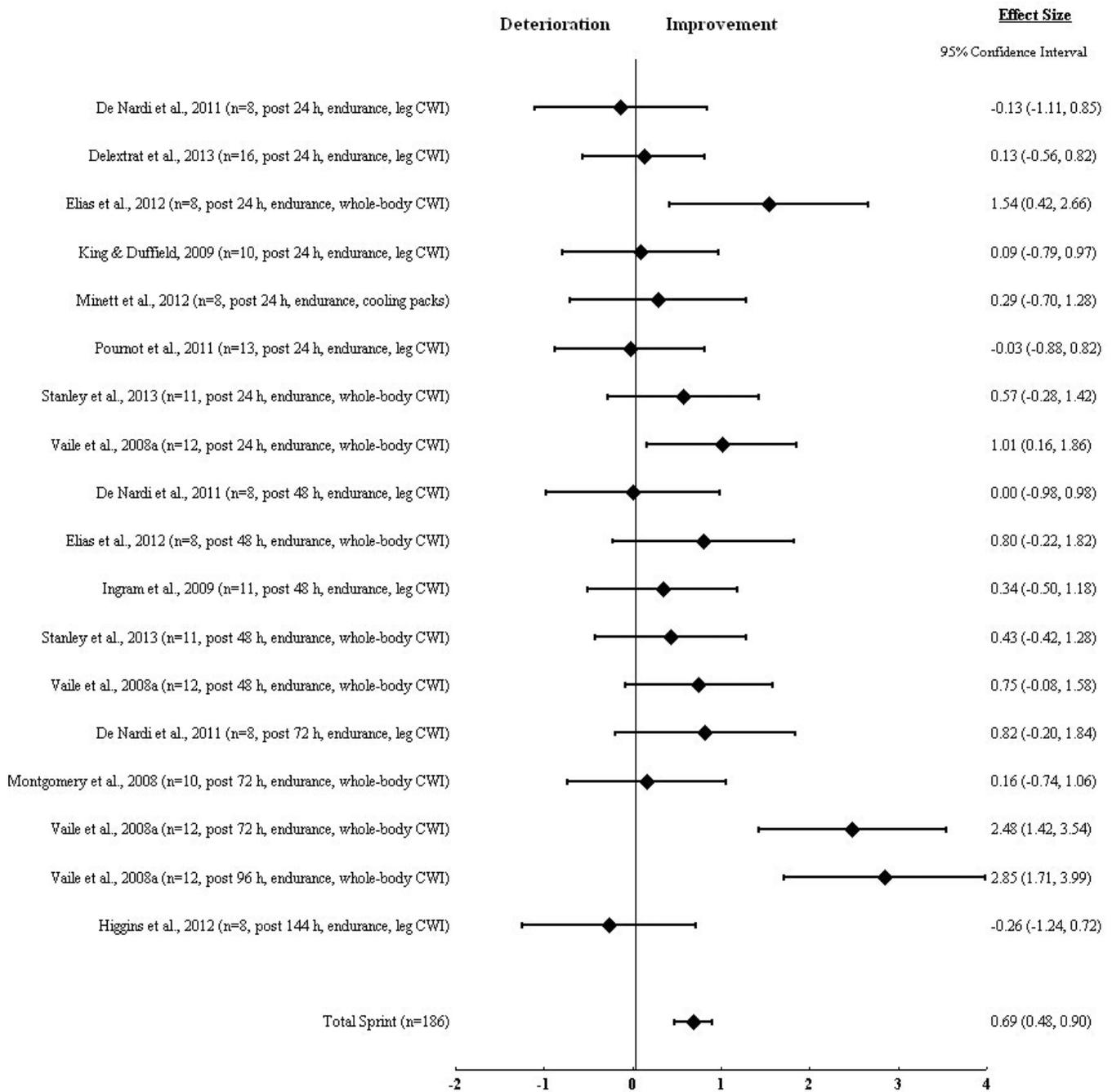


Figure 4 — Effects of cooling after exercise on recovery of sprint performance. For each study, the number of subjects (*n*) and the timing of the posttest (multiple timings possible) are given, as well as the type of exercise to induce fatigue and the cooling method. CWI indicates cold-water immersion.

et al.¹ effects found for strength and jump performance were mostly small or negligible. Thus, it cannot be definitely determined if the observed effects were really due to cooling. In particular, placebo effects might have played a relevant role,⁴⁵ as cooling can hardly be blinded.

Relevant average effect sizes were found only for sprint performance. This is mainly due to the studies by

Vaile et al.²⁸ and Elias et al.²³ showing large effect sizes of up to $g = 2.85$. The reason for these large effects might be the cooling method. In those 2 studies whole-body CWI was used to cool the subjects. Only 1 of the other studies investigating sprint applied whole-body CWI, and that study found the largest effects among the remaining studies.³⁹ All other studies used partial-body CWI.

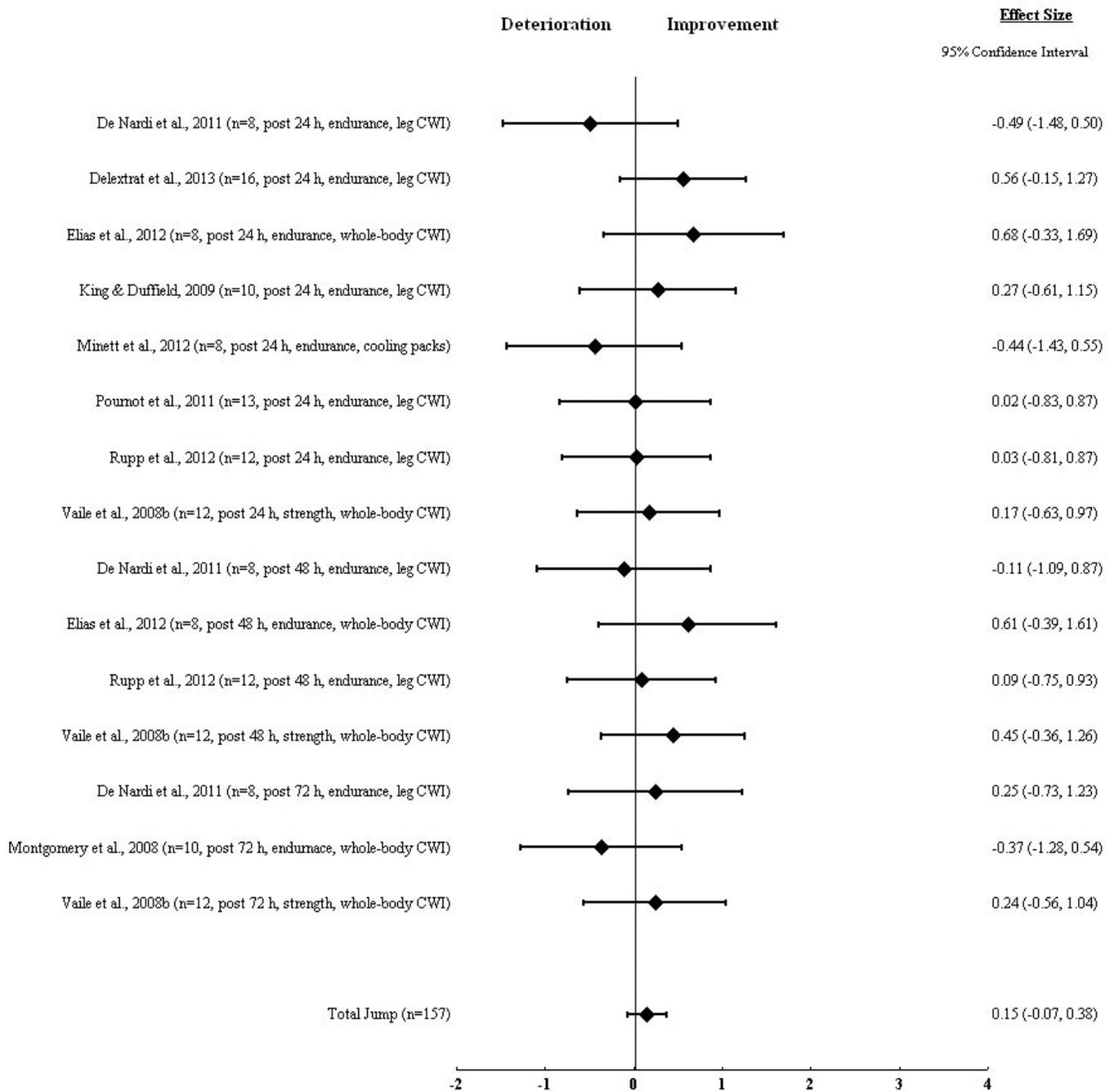


Figure 5 — Effects of cooling after exercise on recovery of jump performance. For each study, the number of subjects (*n*) and the timing of the posttest (multiple timings possible) are given, as well as the type of exercise to induce fatigue and the cooling method. CWI indicates cold-water immersion.

Without the 2 studies showing large effects,^{23,28} average effect size for sprint is $g = 0.20$ and thus similar to the values observed for the other performance components. Therefore, it might be suggested that sprint performance does not, per se, benefit more from cooling than other performance components and that the larger effect sizes found for sprint are, rather, due to other aspects in the study design (such as cooling method). However, apart

from sprint, Vaile et al²⁸ and Elias et al²³ also investigated endurance and jump performance, respectively. There, only small²⁸ and medium²³ effects were found.

Sprint performance mainly depends on muscle strength and neuromuscular coordination.⁴⁶ As only negligible average effects were found for strength performance, it might be speculated that cooling has an effect on recovery of neuromuscular coordination.

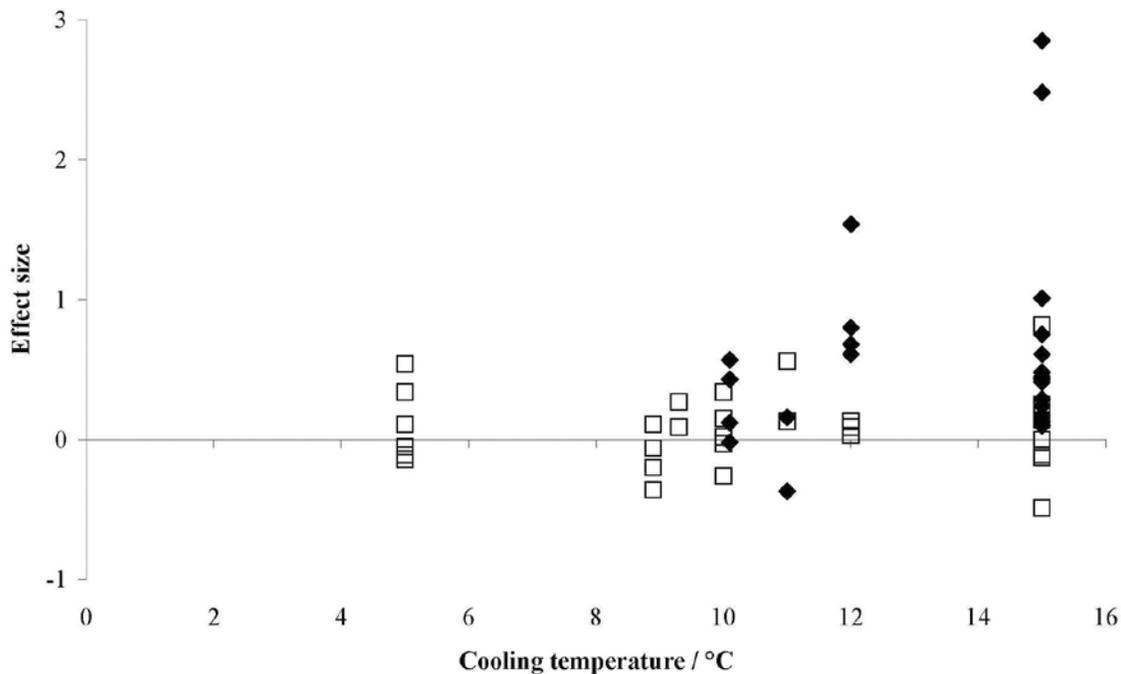


Figure 6 — Effects of cold-water immersion (CWI) after exercise on performance recovery with respect to water temperature. Black diamonds indicate whole-body CWI; white squares, part-body CWI.

Cooling Method

With respect to the cooling method, the largest average effects were found for CWI. This method seems to have become established as some kind of standard, probably because it is the most efficient method for body cooling,⁴⁷ with measured cooling rates in the range of 0.15°C to 0.35°C/min.^{48,49}

On average, whole-body CWI was significantly more effective than cooling only parts of the body. Immersing only a small part of the body (usually the exercised limbs) does not cool down the body core as efficiently as whole-body CWI.⁴⁷ Therefore, temperature effects can be expected to be larger for whole-body CWI. Furthermore, the compressive forces that the water exerts on the body during water immersion (hydrostatic pressure) increase with immersion depth and are therefore larger for whole-body CWI than for partial-body CWI. Independent of temperature effects, the effects of hydrostatic pressure alone may also positively influence postexercise recovery.³ Hydrostatic pressure increases cutaneous interstitial pressure, causing a fluid shift from the interstitial to the intravascular space.⁵⁰ This may reduce edema and possibly secondary tissue damage³ and also increase intracellular–intravascular osmotic gradients, enhancing the clearance of waste products and possibly improving muscle contractile function.^{29,34} Moreover, hydrostatic pressure causes a rise of central blood volume and cardiac output,⁵¹ increasing blood flow and the metabolism of waste products. This effect has been shown to increase with immersion depth.³

Some studies also investigated the effects of postexercise hot-water immersion of the whole body^{28,29} or the legs.³⁸ The 2 studies using whole-body immersion found positive effects of hot-water immersion on performance recovery, but they were smaller than those found for CWI.^{28,29} For leg immersion, negligible effects were observed for both CWI and hot-water immersion.³⁸ These results suggest that for CWI the effects of both hydrostatic pressure and temperature reduction play a role for performance recovery. While the smaller effects found for hot-water immersion may be explained by the exertion of hydrostatic pressure, the additional positive effects found only for CWI seem to be due to the lower water temperature. However, it should be noted that for water temperatures above 36°C,^{28,29} rises in core body temperature can be expected,³ which might also influence recovery.

Regarding the influence of cooling temperature, no clear tendency was visible (see Figure 6). However, it can be concluded that cooling temperatures of 12°C to 15°C are sufficient to elicit positive effects on postexercise recovery and that a further reduction of water temperature is not likely to produce any additional benefit.

While in most of the investigated studies CWI was chosen as the cooling intervention, a few studies used cooling packs or cryogenic chambers. Average effect size when using cooling packs or vests was negative. These results may be explained by the fact that only small parts of the body can be cooled and no hydrostatic pressure is present.

Two studies analyzed the effects of cryotherapy in a cryogenic chamber on muscle-strength recovery.^{24,31} Costello et al³¹ found rather negative effects on perfor-

mance 48 and 72 hours after exercise. Only 96 hours after exercise was a small positive effect observed. In contrast, Hausswirth et al²⁴ observed large percentage improvements of performance (10.8% and 7.4%) with medium effect sizes. The reason for this difference might be that in the study by Costello et al³¹ the subjects did not use the cryogenic chamber until 24 hours after exercise, whereas Hausswirth et al²⁴ applied the cooling chamber immediately after exercise (and again after 24 and 48 h). Therefore, cryotherapy in the study by Costello et al³¹ might have been too late to induce any noteworthy effects on recovery. However, it can be concluded that cryotherapy at -110°C has the potential to positively affect performance recovery.

Further research on postexercise recovery using cryogenic chambers is necessary to determine whether this method might be a reasonable alternative to CWI, especially considering the fact that CWI is much less costly and easier to apply under field conditions than a cryogenic chamber.

Timing of Performance Testing

Halson² investigated the effects of the period between exercise bouts on the efficacy of hydrotherapy and found that for time periods less than 1 hour, significant positive effects of cooling on performance recovery can be expected, especially if exercise is performed in the heat and no short-duration sprinting is involved. However, for periods of 1 hour or less, the beneficial effects are likely due to precooling rather than recovery.^{2,10} As the focus of the current review was on postexercise recovery, studies investigating periods of less than 90 minutes between the fatigue-inducing exercise and the posttest on performance recovery were not analyzed.

For periods of 2 to 3 hours between exercise and posttest, only negligible effects were found in the analyzed studies.^{36,37,40,42} Average effects for 24 hours were slightly larger. Up to a period of 96 hours (4 d), average effects continuously increased with time between exercise and posttest. However, these results might be distorted by the fact that the number of studies for each period decreases continuously from 24 hours to 96 hours. On one hand, several studies showing negligible effects did not test performance for periods longer than 48 hours.^{27,36,37,42} On the other hand, studies showing large effects for all time frames²⁸ have more weight on average effect size for time frames including fewer studies in total. Further indications regarding the influence of the time frame might be obtained by looking at the 3 studies that measured performance at several points of time up to at least 96 hours. In 2 of those,^{28,31} a tendency for increased effectiveness toward longer time frames is visible, while the third³⁵ shows the best results after 48 hours and only negligible effects for larger time frames. For periods longer than 96 hours, it is even more difficult to draw any conclusion, as only 2 studies measured performance after 120 hours or 144 hours.^{35,41} From those results, it appears that cooling no longer has any relevant effects

on performance. One reason might be that after such long periods, performance level has almost returned to baseline values under passive control conditions, making it difficult to see any effects of recovery interventions.³⁵

Effects of cooling were larger if it was applied on a repeated basis (usually once per day). This was most pronounced 72 hours (single cooling, +3.4%, $g = 0.25$; repeated cooling, +2.4%, $g = 0.62$) and 96 hours (single cooling, +2.1%, $g = 0.16$; repeated cooling, +5.9%, $g = 1.64$) after exercise. From these results it can be deduced that to maximize cooling effects after 3 to 4 days, cooling should not only be applied immediately after exercise but also be repeated each day.²

In conclusion, the results indicate that the largest effects of cooling on performance recovery can be expected 2 to 4 days after exercise. This period is of high practical relevance for a variety of competitions, for instance during a soccer season with midweek matches, or for other team sports such as ice hockey or basketball with matches taking place every 2 to 4 days. Considering the positive effects found, particularly for sprint performance, the use of postexercise cooling appears to be beneficial, as sprint performance is one of the key components for this kind of sport.

Fatigue Protocol

With respect to the fatigue-inducing exercise, cooling had larger effects on performance recovery for endurance-type exercise than for strength training. However, when strength exercise was used to induce fatigue, performance tests were usually related to muscle strength. Studies investigating sprint performance (which showed the largest effects) used an endurance-type protocol to induce fatigue. Thus, we cannot finally determine whether the observed differences are due to the type of the fatigue protocol or due to the evaluated performance components. Considering only the results for strength performance, average effect sizes between the 2 types of fatigue protocols differ only slightly ($g = 0.14$ for endurance, $g = 0.08$ for strength). This observation suggests that the differences for the types of fatigue protocol are rather negligible. Similarly, Leeder et al¹ did not find any heterogeneity in this context.

Halson² observed larger effects for weight-bearing exercise than for non-weight-bearing exercise. In the current analysis, contradictory results were found (weight-bearing, +1.9%, $g = 0.15$; non-weight-bearing, +4.0%, $g = 0.76$). This difference might be because Halson investigated water immersion in general (including hot or contrast water), while the current analysis focused on cooling. Moreover, it should be noted that only three^{26,28,39} of the 21 studies applied non-weight-bearing exercise.

Effects of Cooling on Markers of Muscle Damage

Of the 21 studies included, 15 investigated the effects of cooling on postexercise muscle soreness, with 8 studies

reporting that cooling could effectively reduce muscle soreness,^{23–25,33,34,36,38,42} while 7 studies did not find any effects on muscle soreness.^{22,30,31,35,37,39,40} For the studies finding effects on muscle soreness, average effects on performance were larger (+2.1%, $g = 0.21$) than for the studies with no effects on muscle soreness (+1.0%, $g = 0.11$). The effects of cooling on creatine kinase concentration were ambiguous. While 5 studies found that cooling reduced creatine kinase concentration,^{25,29,32,33,38} 2 studies did not find any effects,^{24,36} and 3 studies reported an increase of creatine kinase after cooling compared with the control condition.^{37,40,42}

These results are similar to those of Leeder et al¹ and Bleakley et al,⁵² who identified positive effects of cooling on the reduction of muscle soreness but found only small¹ or no clear effects⁵² on creatine kinase concentration. While the adequacy of creatine kinase concentration as a marker of muscle damage remains unclear,⁵³ it can be concluded that positive effects of cooling on muscle-soreness reduction can be expected.

Conclusions

From the current results, it can be concluded that beneficial effects on performance recovery are possible by cooling intervention subsequent to exercise in trained athletes. By thoroughly analyzing the studies in the literature, we can provide some recommendations for optimized application of cooling to enhance performance recovery (eg, whole-body CWI at temperatures of 12–15°C). However, it must be noted that in the available studies, different cooling methods were combined with different exercise protocols, making it difficult to compare the results. The underlying mechanisms of possible beneficial cooling effects on recovery are not fully understood, and the effects were partly conflicting. Thus, care should be taken by athletes and coaches, particularly, when considering that negative side effects or inhibited training adaptations were also observed when cooling was applied regularly for a longer time frame.⁵⁴

The current analysis has shown that the percentage improvements of performance recovery to be expected from postexercise cooling are large enough to be relevant for competitive athletes. Particularly, for whole-body CWI, cooling-induced improvements of 5% and more can be expected. These gains are clearly above the limits of the smallest worthwhile enhancement as defined by Hopkins et al.^{43,44}

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