Sports Medicine (2021) 51:161–174
https://doi.org/10.1007/s40279-020-01362-0

SYSTEMATIC REVIEW

The Effects of Regular Cold-Water Immersion Use on Training-Induced Changes in Strength and Endurance Performance: A Systematic Review with Meta-Analysis

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Abstract

Background Cold-water immersion (CWI) is one of the main recovery methods used in sports, and is commonly utilized as a means to expedite the recovery of performance during periods of exercise training. In recent decades, there have been indications that regular CWI use is potentially harmful to resistance training adaptations, and, conversely, potentially beneficial to endurance training adaptations. The current meta-analysis was conducted to assess the effects of the regular CWI use during exercise training on resistance (i.e., strength) and endurance (i.e., aerobic exercise) performance alterations.

Methods A computerized literature search was conducted, ending on November 25, 2019. The databases searched were MEDLINE, Cochrane Central Register of Controlled Trials, and SPORTDiscus. The selected studies investigated the effects of chronic CWI interventions associated with resistance and endurance training sessions on exercise performance improvements. The criteria for inclusion of studies were: (1) being a controlled investigation; (2) conducted with humans; (3) CWI performed at ≤ 15 °C; (4) being associated with a regular training program; and (5) having performed baseline and post-training assessments.

Results Eight articles were included before the review process. A harmful effect of CWI associated with resistance training was verified for *one-repetition maximum*, *maximum isometric strength,* and *strength endurance* performance (overall *standardized mean difference* [SMD] = − 0.60; Confidence interval of 95% [CI95%] = − 0.87, − 0.33; $p < 0.0001$), as well as for *Ballistic efforts* performance (overall SMD = − 0.61; CI95% = − 1.11, − 0.11; $p = 0.02$). On the other hand, selected studies verified no effect of CWI associated with endurance training on *time-trial* (mean power), *maximal aerobic power in graded exercise test* performance (overall SMD = − 0.07; CI95% = − 0.54, 0.53; $p = 0.71$), or *time-trial* performance (duration) (overall SMD = 0.00; CI95% = − 0.58, 0.58; $p = 1.00$).

Conclusions The regular use of CWI associated with exercise programs has a deleterious effect on resistance training adaptations but does not appear to affect aerobic exercise performance.

Trial Registration PROSPERO CRD42018098898.

Key Points

Regular use of cold-water immersion decreases strength performance parameters (i.e., one-repetition maximum, maximal isometric strength, strength endurance, and ballistic effort performance).

Cold-water immersion does not affect aerobic exercise performance (i.e., time-trial performance and maximal aerobic power).

Studies involving the regular use of cold-water immersion present moderate methodological quality.

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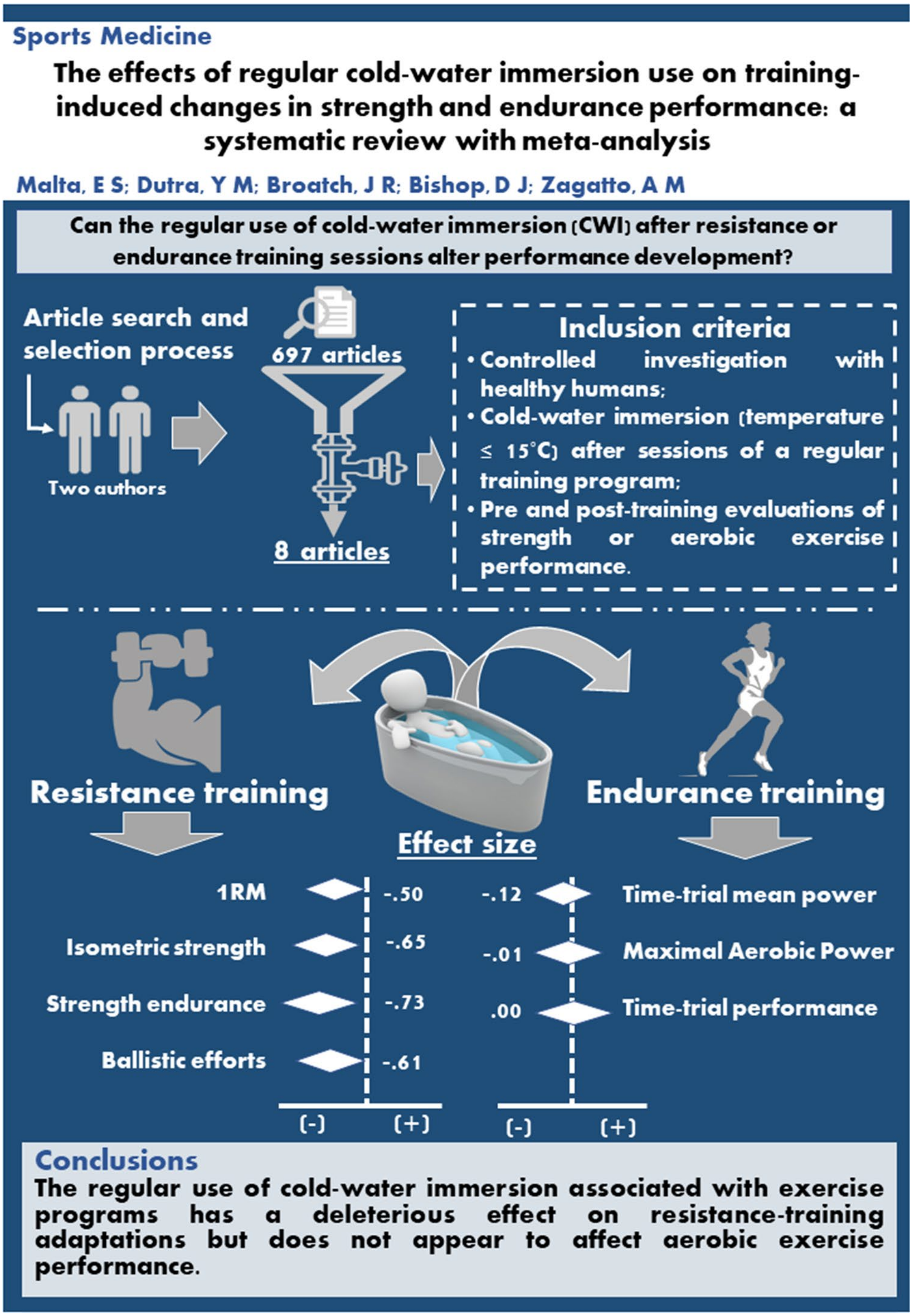
Graphic Abstract



Sports Medicine

The effects of regular cold-water immersion use on training-induced changes in strength and endurance performance: a systematic review with meta-analysis

Malta, E S; Dutra, Y M; Broatch, J R; Bishop, D J; Zagatto, A M

Can the regular use of cold-water immersion (CWI) after resistance or endurance training sessions alter performance development?

Article search and selection process

Two authors

697 articles

8 articles

Inclusion criteria

- Controlled investigation with healthy humans;
- Cold-water immersion (temperature ≤ 15°C) after sessions of a regular training program;
- Pre and post-training evaluations of strength or aerobic exercise performance.

Resistance training

Endurance training

Effect size

Conclusions

The regular use of cold-water immersion associated with exercise programs has a deleterious effect on resistance-training adaptations but does not appear to affect aerobic exercise performance.

Abbreviations

1RM	One-repetition maximum
CI95%	Confidence interval of 95%
CWI	Cold-water immersion
DOMS	Delayed onset muscle soreness
MAP	Maximal aerobic power
mRNA	Messenger ribonucleic acid
PGC-1α	Peroxisome proliferator-activated receptor-γ coactivator-1α
SMD	Standardized mean difference

1 Introduction

Cold-water immersion (CWI) is a widespread method used by athletes and non-athletes in an attempt to aid muscle repair and performance recovery after the stress of exercise [1]. The procedure involves total or partial immersion of the body in ~ 10–15 °C water for 5–20 min [2], preferably immediately after physical efforts [3]. In addition, CWI may also be done as either one continuous [4] or multiple, intermittent sessions [5].

The proposed effects of CWI have been attributed to local vasoconstriction and hydrostatic pressure caused by cold water temperature and water depth [1], respectively. These effects may contribute to physiological alterations such as decreases in metabolic activity [6], hormone secretion [7], infiltration of immune cells [8], and limb blood flow [9–11]. Although there is no consensus [12, 13], these alterations may acutely decrease markers associated with exercise-induced muscle damage and inflammation [3, 7, 14–16], reduce delayed onset muscle soreness (DOMS) [14, 17, 18], and maintain muscle function [16, 19, 20], thereby improving muscle recovery.

Several studies have investigated the effects of regular CWI use (i.e., chronic effect) on training-induced muscle and performance adaptations, including mitochondrial biogenesis, muscle protein synthesis, and muscle repair [4, 21–25]. Initial findings suggested that the effects of regular post-exercise CWI may be task dependent. For example, regular CWI may attenuate training-induced anabolic responses, protein synthesis, and satellite cell activation [23–25], thereby contributing to an attenuation in muscle hypertrophy and strength development, when used during resistance training programs. Conversely, regular CWI may have little to no effect on oxidative signaling pathways when used during endurance training programs [4, 22], consistent with the lack of effect on aerobic exercise performance [4, 26–28].

Most sports incorporate both endurance and resistance training to develop both strength/power and aerobic capacity, as these attributes are associated with sport-specific skills and consequently physical performance [29–31]. The regular use of CWI following training sessions may have important implications for modifying physical performance. However, despite the growing number of reviews in recent years investigating methodological aspects of CWI [1, 18], and the acute effects of CWI on muscle recovery [1, 32], only one narrative review has summarized findings regarding the regular use of CWI in the training routine on long-term muscle adaptations and exercise performance gains [33]. The aim of the present investigation was to systematically review existing research that has investigated the effects of regular CWI on performance adaptations to resistance and endurance training, thereby providing robust evidence-based guidelines for practitioners and/or future research direction.

2 Methods

The present systematic review was guided by the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement [34] and registered in an international database of systematic reviews in health and social care (PROSPERO CRD42018098898). A computerized literature search was conducted, ending on November 25, 2019. The databases searched were MEDLINE, Cochrane Central Register of Controlled Trials (CENTRAL), and SPORTDiscus.

To optimize the search, a strategy of combining the following keyword groups was used: (1) *performance* OR *exercise performance* OR *exercise* OR *trial*; AND (2) *cold-water immersion* OR *cold water immersion* OR *cold water* OR *ice-water immersion* OR *ice water immersion* OR *cooling* OR *ice bath* OR *ice-bath*; AND (3) *chronic* OR *long-term* OR *long term* OR *regular*; NOT (4) *animal* OR *animals*. The restrictions on language (i.e., articles published in English language only) was adopted, while the searches were conducted only on the titles, abstracts, and keyword topics. No year restriction was placed on the search. In addition, references of the selected studies were examined for identification of further eligible studies.

The selected studies were clinical controlled studies that investigated the effects of the regular use of CWI associated with exercise training programs on performance gains (i.e., strength or aerobic exercise performance) in humans. Therefore, books, theses, dissertations, reviews, and conference papers that passed through the initial filter were subsequently excluded. The criteria for inclusion of studies were: (1) being a controlled investigation, (2) conducted with healthy humans, (3) with CWI performed at ≤ 15 °C (after training sessions), (4) being associated with a regular training program (≥ 3 weeks), and (5) having performed baseline and post-training assessments of strength or aerobic exercise performance.

The study selection process was conducted in two stages by two researchers (ESM and YMD). In the first stage, the title and abstract of the selected studies were checked for relevance. In the second stage, the full article text was retrieved and considered for inclusion. If any difference in opinion between researchers was present, the study was discussed in depth until a consensus was achieved. The software Mendeley Desktop 1.17.13 (Elsevier, NY, USA) was used for management of the papers and exclusion of duplicates.

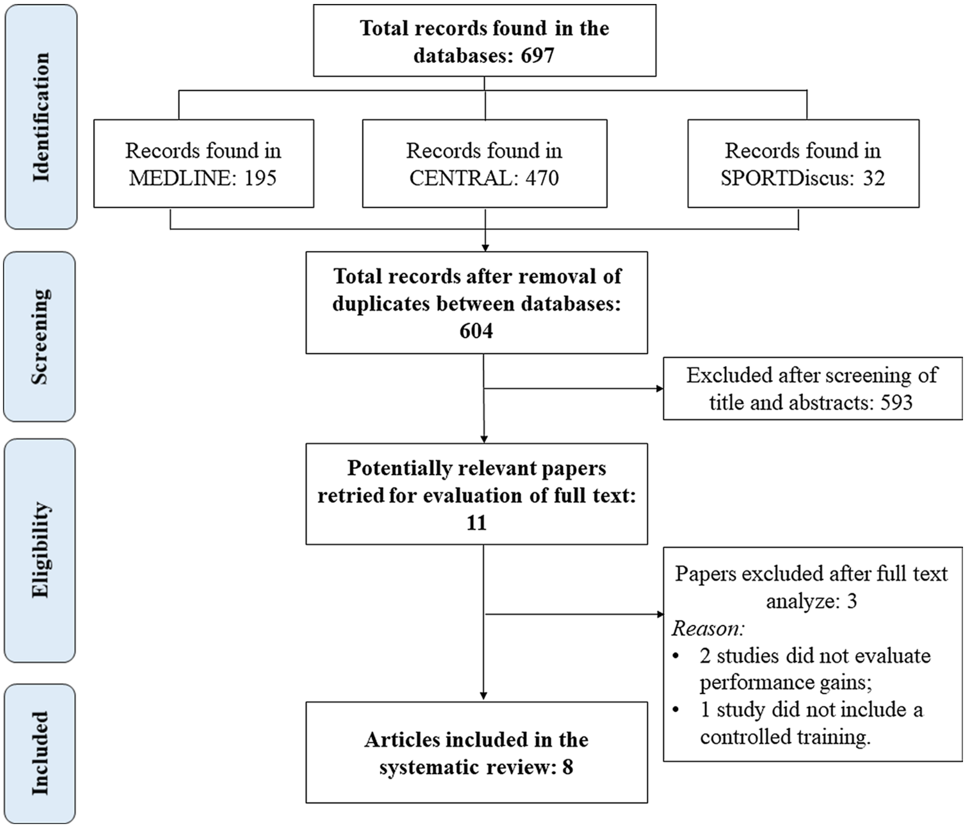


Fig. 1 Flow chart for the selection of studies. *CENTRAL* Cochrane Central Register of Controlled Trials

2.1 Data Extraction

Study data were similarly extracted by two researchers (ESM and YMD), and disagreements between the researchers were mediated as per above. The primary variable/s of interest were exercise performance, namely the change in performance from pre- to post-training, for the intervention (CWI) and control (CON) conditions. The variables related to strength performance were *one-repetition maximum* (*1RM*), *maximal isometric strength, strength endurance* (number of lifts), and *ballistic efforts* (force measured during jump performance and rate of force development), while those related to aerobic exercise performance were *time-trial duration*, *mean power in a time-trial,* and *maximal aerobic power* (*MAP*) in a graded exercise test. In addition, details such as the study design, intervention methods, and training description were also extracted. Relevant data not reported in the manuscript were requested directly from the corresponding author by e-mail and/or via *ResearchGate* private messaging.

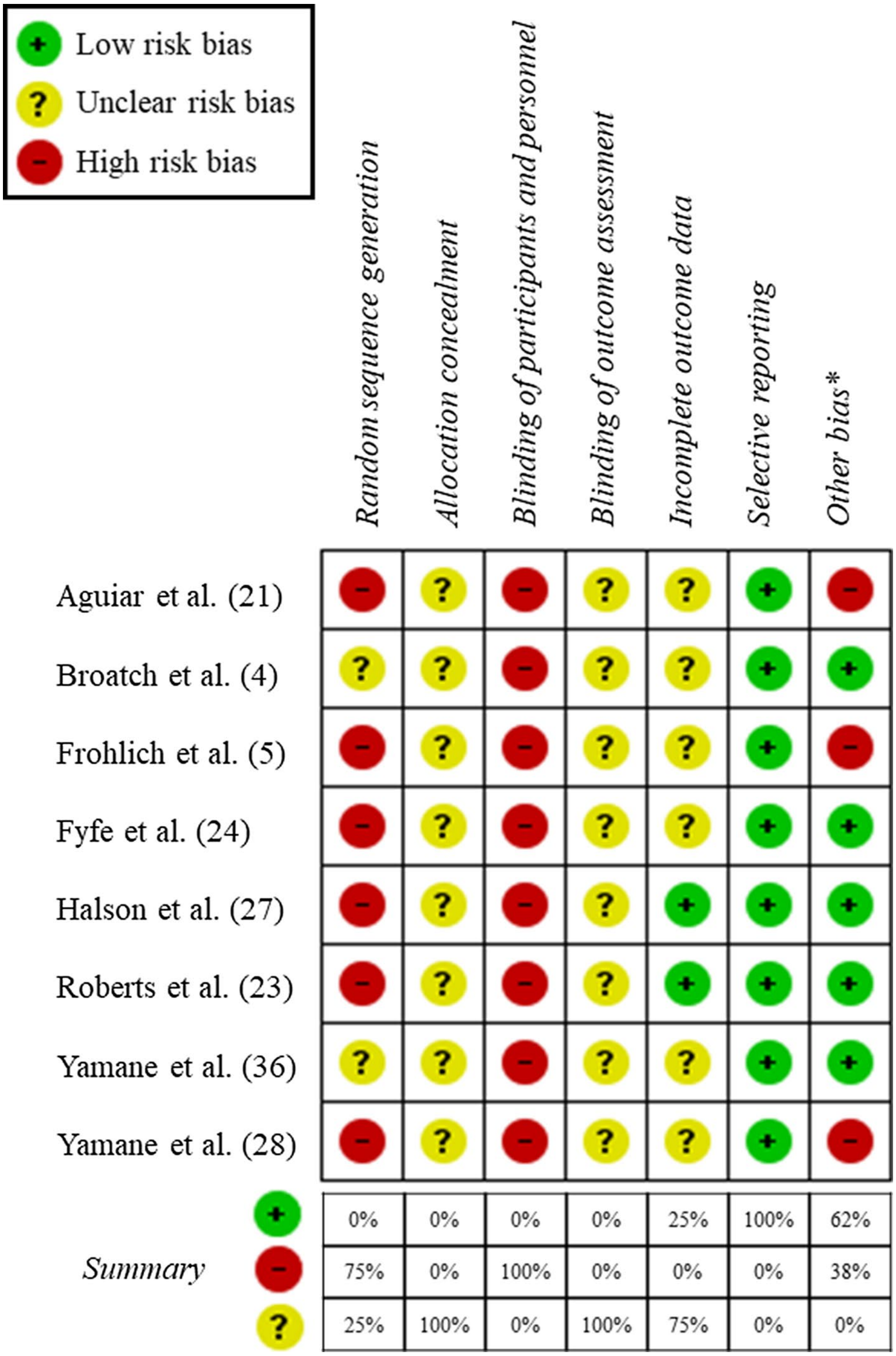
2.2 Quality and Risk of Bias Assessments

The methodological quality of all studies included was assessed using the PEDro-scale considering 11 criteria. The methodological quality of studies was classified according to their respective scores as *high quality* (scores ≥ 7), *moderate quality* (scores 5–6), or *poor quality* (scores ≤ 4). The quality assessment was not used as an inclusion criterion. In addition, the risk of bias analysis for all and individual single studies was calculated according to the Cochrane Collaboration guidelines (RevMan software, version 5.3, Copenhagen, DK). The bias risk was judged as high, low, or unclear, considering five methodological domains (selection, performance, attrition, reporting, and other) [35]. The risk of bias analysis and methodological quality evaluation were performed by two authors (ESM and YMD). As per above, if any difference in opinion between researchers was present, the risk of bias analysis and methodological quality evaluation was discussed until a consensus was achieved.

2.3 Data Analysis

The software Review Manager 5.3 was also used in the statistical analyses and to generate forest plot figures. For all variables, the standardized mean difference (SMD) and 95% confidence intervals (CI95%) were calculated.

Fig. 2 Individual and summarized results for risk of bias of included studies. * "Other bias" in the present study refers to risk of bias associated with study design (with possible cross-talk effect)



+ Low risk bias
? Unclear risk bias
− High risk bias

	Random sequence generation	Allocation concealment	Blinding of participants and personnel	Blinding of outcome assessment	Incomplete outcome data	Selective reporting	Other bias*
Aguiar et al. (21)	−	?	−	?	?	+	−
Broatch et al. (4)	?	?	−	?	?	+	+
Frohlich et al. (5)	−	?	−	?	?	+	−
Fyfe et al. (24)	−	?	−	?	?	+	+
Halson et al. (27)	−	?	−	?	+	+	+
Roberts et al. (23)	−	?	−	?	+	+	+
Yamane et al. (36)	?	?	−	?	?	+	+
Yamane et al. (28)	−	?	−	?	?	+	−
Summary +	0%	0%	0%	0%	25%	100%	62%
−	75%	0%	100%	0%	0%	0%	38%
?	25%	100%	0%	100%	75%	0%	0%

3 Results

In total, 697 articles were identified in the database search (i.e., 195 articles in MEDLINE, 470 in Cochrane Central Register of Controlled Trials (CENTRAL), and 32 in SPORTDiscus). Next, duplicates were excluded, resulting in a total of 604 articles. After analysis of the titles and abstracts, 11 studies were selected for full text analysis. Finally, 8 studies were included in the final review process and data extraction. No studies were added after the reference review process. Figure 1 shows the schematic process of the study selection.

In general, the selected studies presented a *high* risk of bias, mainly in the randomization and blinding process. The majority of the investigations did not present explicit information about the method used in the randomization (e.g., coin tossing, shuffling cards or envelopes, throwing dice, and drawing lots) and the allocation concealment. In addition, no investigations were blinded (i.e., single-blinding or double-blinding) and only two presented explicit information

Table 1 Characteristics and results of the included studies

Study, year; Funding	Study design	CWI and CON configuration	No. of training sessions/duration (frequency)	Training description	Performance assessment	Performance changes (mean difference to pre)	Data source	PEDro scale *score*
Resistance training								
Frohlich et al. [5], 2014; NF	Crossover group	CWI: 3 × 4 min (intervals: 30 s) in 12.0 ± 1.5 °C; standing, 1-leg immersion	~ 15 sessions/5 weeks (1–3 × /week)	Unilateral leg exercises: 3 sets of 8–12 repetitions with 3 min of rest at 75–80% of 1RM	1RM knee extension	CWI: + 7.2 ± 7.3 kg	Provided by the author	5
		CON: passive recovery				CON: + 9.3 ± 7.8 kg		
Roberts et al. [23], 2015; GIF	Parallel groups	CWI: 10 min in 10.1 ± 0.3 °C; seated, both legs immersed	24 sessions/12 weeks (2 × /week)	Leg extensions and flexions: 3–6 sets of 8–12 repetitions	1RM knee extension	CWI: + 17.8 ± 9.2 kg	Provided by the author	6
		CON: active recovery				CON: + 33.8 ± 8.5 kg*		
				Plyometric exercises: 3 sets of 12 repetitions	1RM Leg press	CWI: + 133.0 ± 43.5 kg		
						CON: + 201.0 ± 65.2 kg*		
					Maximal isometric knee-extension strength	CWI: + 2.5 ± 3.9 kg		
						CON: + 6.6 ± 3.3 kg*		
					Knee-extension RFD impulse	CWI: + 115.1 ± 79.6 Nm/s		
						CON: + 301.4 ± 134.5 Nm/s*		
Yamane et al. [36], 2015; GIF	Parallel groups	CWI: 20 min in 10 ± 1 °C; arm horizontal, 1 lower arm	12 sessions/4 weeks (3 × /week)	Wrist-flexion exercises: 5 sets of 8 repetitions at 70–80% of 1RM;	Maximal isometric strength for wrist flexion	CWI: + 0.69 ± 3.5 kg	Provided by the author	5
		CON: passive recovery (1 lower arm of the same volunteer)				CON: + 6.04 ± 3.6 kg*		
					Number of lifts of wrist flexion	CWI: + 14.1 ± 9.4 lifts		
						CON: + 19.4 ± 6.3 lifts		
Yamane et al. [28], 2006; EF and GIF	Crossover Group (part III)	CWI: 20 min in 10 ± 1 °C; arm horizontal, 1 lower arm	12 sessions/4 weeks (3 × /week)	Handgrip exercises: 3 sets of 8 RM with 2-min rest periods	Maximal isometric strength for wrist flexion	CWI: + 4.1 ± 4.45 kg	Provided by the author	5
		CON: passive recovery (1 lower arm of the same volunteer)				CON: + 5.86 ± 5.25 kg		
					Number of lifts of wrist flexion	CWI: + 16.2 ± 34.0 lifts		
						CON: + 53.1 ± 46.1 lifts*		
	Parallel groups (part IV)	CWI: 20 min in 10 ± 1 °C; arm horizontal, lower arms	12 sessions/4 weeks (3 × /week)	Handgrip exercises: 3 sets of 8 RM with 2-min rest periods;	Maximal isometric strength for wrist flexion	CWI: + 0.21 ± 3.7 kg		

Table 1 (continued)

Study, year; Funding	Study design	CWI and CON configuration	No. of training sessions/duration (frequency)	Training description	Performance assessment	Performance changes (mean difference to pre)	Data source	PEDro scale *score*
		CON: passive recovery				CON: + 0.75 ± 5.0 kg		
					Number of lifts of wrist flexion	CWI: + 43.8 ± 26.1 lifts		
						CON: + 72.8 ± 56.8 lifts		
Fyfe et al. [24], 2019; GIF	Parallel groups	CWI: 15 min in 10 °C; seated, whole-body immersion (up to sternum)	21 sessions/7 weeks (3 × /week)	Lower- and upper-limb extensors and flexors: 3 sets of 12 repetitions at 12-RM	1RM Leg press	CWI: + 39.2 ± 25.1 kg	Provided by the author	6
		CON: 23 °C for 15 min				CON: + 37.9 ± 18.8 kg		
					1RM Bench press	CWI: + 11.7 ± 12.2 kg		
						CON: + 8.6 ± 8.4 kg		
				Abdominal: 3 sets of 20 repetitions at 20-RM	Ballistic push-up	CWI: + 0.9 ± 59.9 N		
						CON: + 3.4 ± 54.2 N		
				Back squat and barbell bench press: 5 sets of 12 repetitions at 12-RM	CMJ	CWI: − 61.8 ± 103.3 N		
						CON: + 98.0 ± 101.9 N		
					SJ	CWI: − 21.1 ± 223.5 N		
						CON: + 131.7 ± 240.4 N		
Endurance training								
Halson et al. [27]], 2014; GIF	Parallel groups	CWI: 15 min in 15 ± 3° C; whole-body immersion (up to shoulder)	39 sessions /~ 5.5 weeks (7 × / week)	SIT + specific cycling efforts [2 repetitions of 4-min maximal effort following by short repeated sprints (6–20 s), pursuit and time-trial efforts)	10-min time-trial mean power	CWI: + 5.4 ± 3.7%	Extracted from the text	5
		CON: passive recovery				CON: + 5.9 ± 2.8%		
Aguiar et al. [21], 2016; GIF	Parallel groups	CWI: 15 min in 10 ± 1 °C; standing, both legs immersed	12 sessions/4 weeks (3–4 × /week)	Long HIIT: 1-min cycling effort followed by 75 s of rest	MAP in a Graded exercise test	CWI: + 23.4 ± 13.4 W	Provided by the author	5
		CON: passive recovery				CON: + 6.6 ± 33.6 W		
					15-km time-trial	CWI: − 4.7 ± 1.8 min		
						CON: − 4.2 ± 2.0 min		
					15-km time-trial mean power	CWI: + 17.2 ± 7.7 W		

Table 1 (continued)

Study, year; Funding	Study design	CWI and CON configuration	No. of training sessions/duration (frequency)	Training description	Performance assessment	Performance changes (mean difference to pre)	Data source	PEDro scale *score*
						CON: + 16.6 ± 5.8 W		
Broatch et al. [4], 2017; GIF	Parallel groups	CWI: 15 min in 10 °C; seated, both legs immersed	18 sessions/6 weeks (2–3 × /week)	SIT: 4–6 repetitions of 30-s "all-out" cycling sprints following by 4 min of rest	MAP in a Graded exercise test	CWI: + 15.4 ± 12.7 W	Provided by the author	6
		CON: passive recovery				CON: + 15.2 ± 13.1 W		
					2-km time-trial	CWI: − 0.11 ± 0.16 min		
						CON: − 0.09 ± 0.11 min		
					20-km time-trial	CWI: − 0.42 ± 1.21 min		
						CON: − 0.53 ± 1.5 min		
					2-km time-trial mean power	CWI: + 15.6 ± 23.4 W		
						CON: + 22.2 ± 35.0 W		
					20-km time-trial mean power	CWI: + 4.1 ± 11.1 W		
						CON: + 7.6 ± 19.2 W		
Yamane et al. [28], 2006; EF and GIF	Crossover Group (part I)	CWI: 2 × 20 min (interval: 30 min) in 5 ± 1 °C; Prone position, 1-leg immersed (thigh and lower leg)	16 sessions/4 weeks (4 × /week)	Moderate-intensity continuous training: 25-min cycling effort at 70% of the maximal oxygen uptake intensity	MAP in a Graded exercise test	CWI: + 10.0 ± 8.4 W	Provided by the author	
		CON: passive recovery (1-leg of the same volunteer)				CON: + 16.0 ± 10.0 W		
	Crossover Group (part II)	CWI: 20 min in 5 ± 1 °C; Prone position, 1-leg immersed (thigh and lower leg)	24 sessions/6 weeks (4 × /week)	Moderate-intensity continuous training: 25-min cycling effort at 70% of the maximal oxygen uptake intensity	MAP in a Graded exercise test	CWI: + 19.2 ± 9.7 W		
		CON: passive recovery (1-leg of the same volunteer)				CON: + 21.7 ± 11.3 W		

CWI cold-water immersion, *CON* control group, *1RM* one-maximal repetition, *HIIT* high-intensity interval training, *SIT* sprint interval training, *MAP* maximal aerobic power, *RFD* rate of force development, *CMJ* counter movement jump, *SJ* Squat jump, *NF* no external funding, *EF* external funding, *GIF* government and/or institutional funding

*$p < 0.05$ between groups

about the sample loss (i.e., incomplete outcome data). On the other hand, all investigations demonstrated appropriate outcome reporting (i.e., without selective reporting) and five investigations did not present other limitations. Figure 2 presents the individual and general results of the risk of bias judgment.

Among the eight articles selected for the present study, one was performed in Brazil [21], four in Australia [4, 23, 24, 27], two in Japan [28, 36], and one in Germany [5], and all were published between the years 2006 and 2019. The study volunteers were healthy men classified as trained [27], physically active [5, 21, 23], recreationally active [4, 24, 36], or sedentary [28] (total number including CWI and control groups = 470 volunteers).

Table 1 presents the selected studies, methodological parameters, results, and their PEDro quality score. Regarding the control groups, passive recovery (i.e., resting at room temperature) [4, 5, 21, 27, 28, 36], active recovery (i.e., 10 min of low-intensity exercise on a cycle ergometer) [23], or water immersion in a neutral temperature (15 min at 23 °C) [24] were performed. The CWI temperature and duration were 9.7 ± 2.9 °C and 16.5 ± 3.6 min, respectively. In addition, two studies divided the CWI application into 2 sets of 20 min [28] and 3 sets of 4 min [37]. The training programs used in the selected studies were plyometric and/or hypertrophy training (resistance training) [5, 23, 24, 28, 36], moderate-intensity continuous training, high-intensity interval training or sprint interval training (endurance training) [4, 21, 27, 28], while the number of sessions was 16 ± 5 sessions for resistance training and 22 ± 11 sessions for endurance training. The methodological quality of the studies included showed a mean of 5.3 arbitrary units (indicating *moderate quality*), of which *blinding* was the criterion most commonly not contemplated in these studies since CWI is readily perceived by volunteers and conventional blinding is not applicable in this case.

For the analysis of the effect of CWI on resistance training performance metrics, five studies were used [5, 23, 24, 28, 36], of which five provided data related to *1RM*, three included *maximal isometric strength*, two included *strength endurance,* and two included *ballistic efforts*. Decreases in performance gains were verified for *1RM* (SMD = − 0.50; CI95% = − 0.90, − 0.10; $p = 0.01$), *maximal isometric strength* (SMD = -0.65; CI95% = − 1.14, − 0.17; $p = 0.009$), and *strength endurance* (SMD = − 0.73; CI95% = − 1.29, − 0.16; $p = 0.01$), when resistance training was performed followed by CWI (overall SMD = − 0.60; CI95% = − 0.87, − 0.33; $p < 0.0001$) (Fig. 3). In addition, decrease in performance gains were verified for the performance of *ballistic efforts* (overall SMD = − 0.61; CI95%: − 1.11, − 0.11; p = 0.02).

For the analysis of the effect of CWI on endurance training performance metrics, four studies were used [4, 21, 27, 28], of which two provided data related to *time-trial performance* (mean power), three related to *MAP* in a graded exercise test, and three included *time-trial performance* (time). No changes in performance were verified for *time-trial performance* (mean power) (SMD = − 0.12; CI95% = − 0.60, 0.36; $p = 0.63$), or *MAP* (SMD = − 0.01; CI95% = − 0.54, 0.53; $p = 0.98$), when endurance training was performed with CWI (overall SMD = − 0.07; CI95% = − 0.54, 0.53; $p = 0.71$). In addition, no changes in gains were verified for *time-trial* performance (time) (overall SMD = 0.00; CI95% = − 0.58, 0.58; $p = 1.00$) (Fig. 4).

4 Discussion

The main findings from this systematic review were that CWI mitigates training-induced improvements in maximum strength or strength endurance (overall SMD = − 0.60; $p < 0.0001$), but has no effect on training-induced improvements in aerobic exercise performance (overall SMD = − 0.07; $p = 0.71$). Regarding the effects of CWI on muscle strength, it is noteworthy that gains in all strength parameters investigated (i.e., *1RM*, *maximal isometric strength*, *strength endurance, and ballistic efforts*) were reduced by CWI.

During a resistance training program, maximal strength (assessed by *1RM* and *maximal isometric strength)* and the performance of *ballistic efforts* may be altered via a combination of neurological (e.g., learning and coordination) and morphological adaptations (e.g., increases in muscle cross-section area, myofibrillar size, and myofibrillar number [38]), assisted by alterations in numerous molecular mechanisms/pathways (e.g., muscle protein synthesis, satellite cell activation/proliferation, etc.). Similarly, strength endurance (i.e., the ability to withstand fatigue under conditions of extended force performance) is related to some morphological adaptations (e.g., improved mitochondrial function, increased capillary density, improved buffer capacity, etc.) and may also be affected by muscle repair and protein synthesis processes [39]. Therefore, should CWI alter any of these training-induced processes, it is likely to influence the muscle's adaptive response to exercise and subsequently exercise performance.

Consistent with the aforementioned, Roberts et al. [23] reported that regular CWI following resistance training attenuated the training-induced increases in type II muscle fiber cross-sectional area and the number of myonuclei per fiber, compared with a control group (active recovery). In addition, CWI acutely delayed and/or inhibited satellite cell activity, suppressed phosphorylation of proteins associated with hypertrophy, and mitigated *1RM* and *maximal isometric strength* improvements. Cooling has been reported to decrease regulatory factors associated with myogenesis (e.g., myogenin), and consequently impair skeletal muscle growth [40] and strength development [41]. In a subsequent study, Fyfe et al. [24] also reported a blunting of training-induced increases in skeletal muscle fiber hypertrophy, but no effect on *1RM* performance. These results were not unexpected, as hypertrophy is not always accompanied by strength increases [42]. In addition, differences in hypertrophy and strength outcomes between studies may be explained by differences in the training prescription variables (e.g., effort-pause ratio, *1RM* percentage related load, training frequency, and duration, etc.), which play a large role in the adaptive response to resistance training [39]. For example, Roberts et al. [20] submitted the volunteers to 12 weeks (2 × week) of lower-limb resistance training (3–5 sets of 8–12 repetitions at 8–12-RM), as well as plyometric efforts (3 sets of 12 ballistic efforts), while the study of Fyfe et al. [24] included 7 weeks (2 × week) of lower- and upper- limb training (3–5 sets of 12 repetitions at 1–12-RM) and abdominals (3 sets of 20 repetitions at 20-RM). Therefore, in addition to training duration and frequency, there are some important differences in the number of sets and the training composition (e.g., only Roberts et al. [23] performed plyometric efforts).

Another explanation for cold-induced reductions in strength are that CWI induces a vasoconstrictive response and a subsequent reduction in blood flow [9]. Considering blood flow is correlated with muscle protein synthesis [43], and a positive muscle protein synthesis/breakdown balance is important for hypertrophy and strength development [44], this may also explain why CWI attenuates training-induced strength adaptations. In this context, Fuchs et al. [25] reported that myofibrillar protein synthesis rates were decreased when CWI was performed following resistance training (combined with protein ingestion), which is likely explained by a reduction in the delivery and/or uptake of protein after resistance training. This was hypothesised to be due to decreased amino acid transport or lower blood supply, although this hypothesis has not yet been investigated.

The use of regular CWI during endurance training programs (e.g., high-intensity interval training, sprint interval training, and/or moderate-intensity continuous training) appears to have no effect on gains in aerobic exercise performance, regardless of the performance metric used (e.g., MAP during a graded exercise test or time-trial performance). Aerobic exercise performance is primarily related to factors such as an individual's maximal oxygen uptake, running economy, and lactate threshold [45–47], which are influenced by skeletal muscle adaptations that include increases in mitochondrial density [48] and greater aerobic enzyme activity [49]. These adaptations have been proposed to arise from homeostatic perturbations in response to exercise (i.e., changes in primary messengers, such free fatty acids, lactate, calcium, the redox state of the cell, reactive oxygen species, and adenosine triphosphate turnover). These changes may activate secondary messenger proteins, such as calcium/calmodulin-dependent kinases II, 5′ AMP-activated protein kinase, p38 mitogen-activated protein kinases, and sirtuin 1. These secondary messengers subsequently activate transcription factors, which initiate gene transcription and the translation/synthesis of functional proteins. For a more detailed account of this process, please refer to some excellent reviews on this topic [48, 50, 51].

Although CWI does not affect performance gains in response to endurance training [4, 21, 27, 28], some investigations have reported post-exercise CWI to augment exercise-induced increases in the gene expression of key endurance training regulatory proteins, such as proliferator-activated receptor gamma coactivator-1α mRNA (PGC-1α mRNA) [52–54]. However, it is important to note that there is not always a strong correlation between changes in gene expression and subsequent increases in functional protein content [55], which may help explain the absence of effects on aerobic exercise performance [4, 21, 27, 28]. In support of this, mRNA transcript abundance is only partially correlated with protein abundance ($r = \sim 0.40$) [56]. Only one study to date has reported regular CWI to augment muscle content of endurance-related proteins (e.g., PGC-1α) [22]; however, performance outcomes were not evaluated in this study due to the experimental design used (i.e., CWI was performed in one leg, while the contralateral leg remained outside the cold-water bath [control]).

Another potential explanation for the lack of effect of CWI on aerobic exercise performance is that peripheral changes in muscle aerobic function/oxidative capacity are likely to have smaller effects on aerobic performance when compared with central adaptations [57]. Furthermore, central limitations in aerobic endurance exercise are more common in trained participants, while peripheral limitations are more likely in untrained participants (e.g., peripheral circulation and muscle metabolism) [58]. While there were not a sufficient number of studies to investigate the influence of training level, future studies should investigate the effects of CWI in participants with different training levels.

It is commonly hypothesised that regular CWI use during training will accelerate short-term recovery [14, 18, 59–61], and thereby contribute to maximizing the adaptive response after a training program. However, the lack of additional improvements in aerobic performance, and the attenuation of strength performance, reported in the current review are contrary to this hypothesis. Therefore, evidence regarding the positive acute effects of CWI on "recovery parameters" (e.g., markers of muscle damage and/or inflammation, DOMS, and muscle performance) do not seem to contribute to greater long-term adaptations to training. For example, acute reductions in the post-exercise inflammatory response following a single exercise session and CWI have

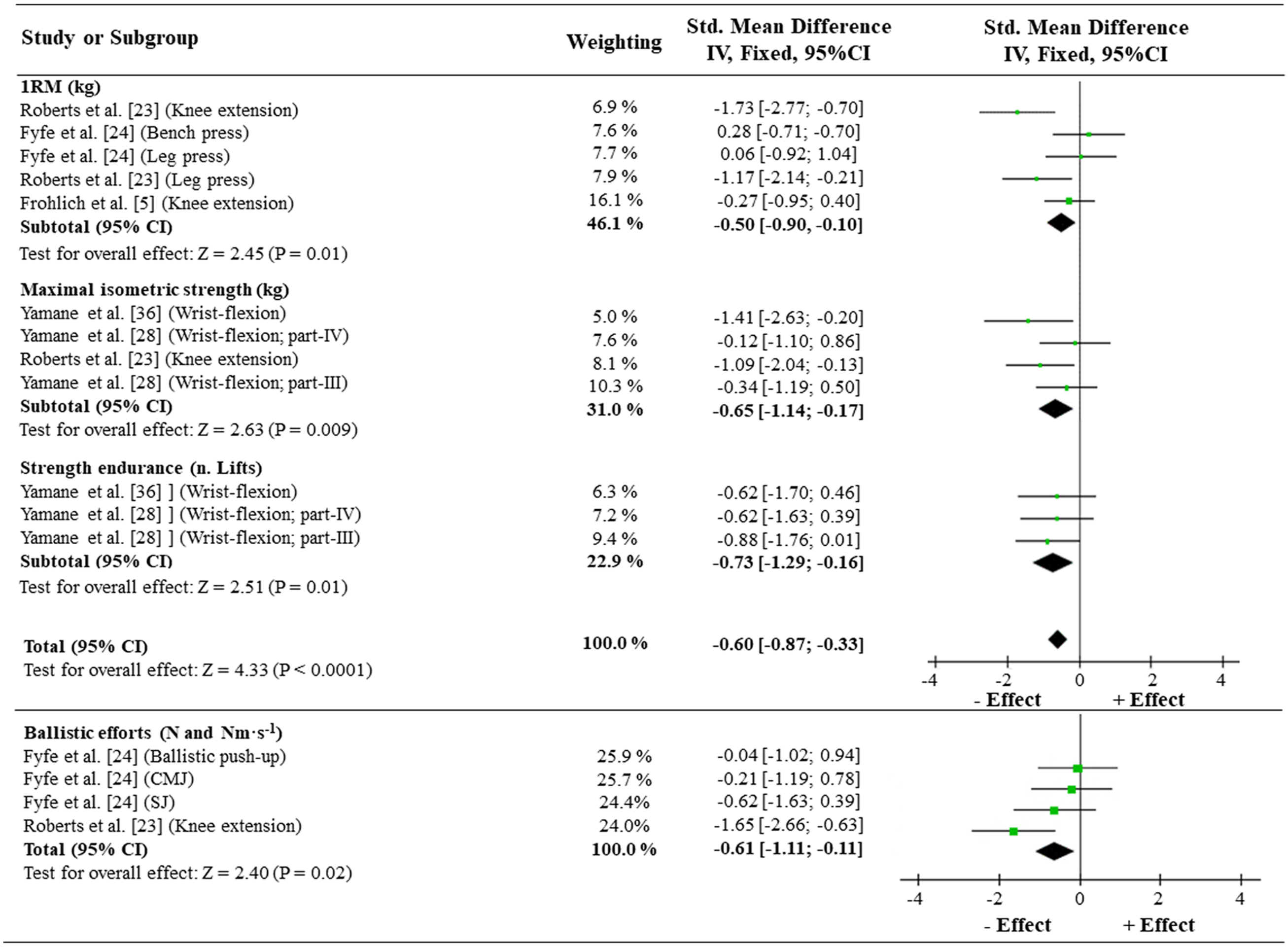


Fig. 3 Forest plot of the meta-analysis illustrating the comparison between CWI and the control condition for strength parameters. *CWI* cold-water immersion, *CI* confidence interval

been interpreted as positive [14]; however, inflammation is an important component of the muscle repair process [62] and limiting inflammation may be counterproductive for long-term training adaptations [62, 63]. As such, while CWI may be beneficial in the recovery of performance in the short term, it does not seem to benefit adaptations to training. In this manner, "recovery periodization" may be an important approach in sport training programs. For example, it may be advisable to avoid CWI during training blocks focused on improving strength, hypertrophy, and power. It could also be suggested that CWI may be most beneficial when used during competition when heavy resistance training is not typically performed [64, 65] and slow physiological recovery may compromise subsequent performance [66].

A number of limitations in this research area have been identified as a result of this systematic review. For example, there is a large heterogeneity in the parameters of CWI application, namely the time of exposure and water temperature. Acute beneficial effects of CWI on muscle recovery have typically been reported when performed at 11–15 °C and for 11–15 min, which is thought to be the optimal CWI temperature and duration to reduce pain perception and to improve muscle function [18]. In the studies selected for the present review, the CWI temperature was 9.7 ± 2.9 °C, and the exposure time was 16.5 ± 3.6 min. However, it is unclear whether this CWI temperature and duration are optimal for regular CWI during exercise training. It may be that different water temperatures are required to enhance the acute recovery of muscle performance than to facilitate adaptations to training.

It is also important to highlight the large variance in training and CWI durations used; some interventions [23, 24] were over ~ 2–3 times longer in duration that others [4, 5, 21, 27, 28, 36]. These methodological differences make direct comparisons between studies difficult, and it is possible that the varying training and CWI stimuli administered to participants had varying effects on the performance metrics measured. For example, it is expected that 39 endurance training sessions [27] would have a greater accumulative effect on aerobic exercise performance than

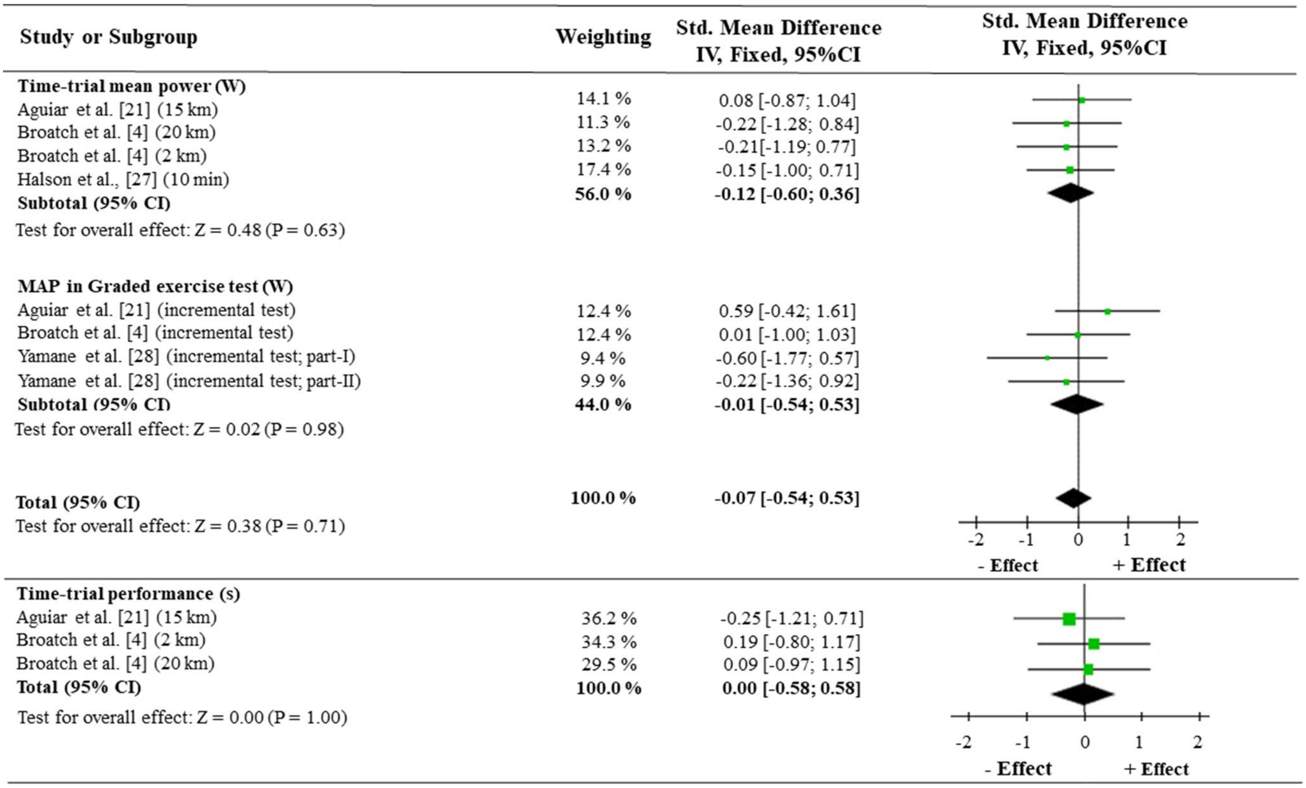


Fig. 4 Forest plot of the meta-analysis illustrating the comparison between CWI and the control condition for aerobic endurance parameters. *CWI* cold-water immersion, *CI* confidence interval, *MAP* maximal exercise test

12 endurance training sessions [21], provided there was adequate training progression. Finally, the quality of the selected studies in the current systematic was classified as *moderate,* mainly due to the difficulty of blinding. In addition, the studies presented a high risk of bias due to the difficulty of blinding and problems in describing the randomization. Therefore, a possible placebo effect of this method should not be discarded in this type of procedure. For example, a CWI placebo (administered by deception) has previously been reported to be as effective as CWI, and more effective than a thermo-neutral control immersion [12]. As such, investigations could improve the quality of their studies by including a placebo condition, which in turn would strengthen the CWI literature as a whole.

5 Conclusion

In summary, the regular use of post-exercise CWI does not appear to influence performance adaptations associated with aerobic exercise training. However, there is contrary evidence reporting that CWI has a deleterious effect on muscle strength gains associated with resistance exercise training. Considering the scarcity of research investigating the effects of regular CWI on performance adaptations following exercise training, more high-quality research is needed. For example, more research investigating the molecular mechanisms regulating skeletal muscle adaptation following regular post-exercise CWI, the role exercise prescription variables (i.e., frequency, intensity, duration, and type) play on attenuating or augmenting these adaptations, and/or the optimal parameters of CWI application to optimize these adaptations, are warranted.

Author contributions ESM, YMD and AMZ contributed to the study conception, design, material preparation, data collection and analysis. ESM, YMD, JRB, DJB, and AMZ contributed to data interpretation and manuscript writing. All authors read and approved the final manuscript.

Compliance with Ethical Standards

Conflict of interest Elvis Malta, Yago Dutra, James Broatch and David Bishop declare no conflicts of interest.

Funding Elvis de Souza Malta was supported by São Paulo Research Foundation (FAPESP) fellowship (no. 2017/21724-8). This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Code availability Not applicable.

References

1. Wilcock IM, Cronin JB, Hing WA. Water immersion: does it enhance recovery from exercise? Int J Sports Physiol Perform. 2006;1:195–206.
2. Peiffer JJ, Abbiss CR, Watson G, Nosaka K, Laursen PB. Effect of cold-water immersion duration on body temperature and muscle function. J Sports Sci. 2009;27:987–93.
3. Brophy-Williams N, Landers G, Wallman K. Effect of immediate and delayed cold water immersion after a high intensity exercise session on subsequent run performance. J Sports Sci Med. 2011;10:665–70.
4. Broatch JR, Petersen A, Bishop DJ. Cold-water immersion following sprint interval training does not alter endurance signaling pathways or training adaptations in human skeletal muscle. Am J Physiol Regul Integr Comp Physiol. 2017;313:R372–84.
5. Frohlich M, Faude O, Klein M, Pieter A, Emrich E, Meyer T. Strength training adaptations after cold-water immersion. J strength Cond Res. 2014;28:2628–33.
6. Ihsan M, Watson G, Lipski M, Abbiss CR. Influence of postexercise cooling on muscle oxygenation and blood volume changes. Med Sci Sports Exerc. 2013;45:876–82.
7. Earp JE, Hatfield DL, Sherman A, Lee EC, Kraemer WJ. Cold-water immersion blunts and delays increases in circulating testosterone and cytokines post-resistance exercise. Eur J Appl Physiol. 2019;119:1901–7.
8. Lee H, Natsui H, Akimoto T, Yanagi K, Ohshima N, Kono I. Effects of cryotherapy after contusion using real-time intravital microscopy. Med Sci Sports Exerc. 2005;37:1093–8.
9. Mawhinney C, Jones H, Low DA, Green DJ, Howatson G, Gregson W. Influence of cold-water immersion on limb blood flow after resistance exercise. Eur J Sport Sci. 2017;17:519–29.
10. Mawhinney C, Jones H, Joo CH, Low DA, Green DJ, Gregson W. Influence of cold-water immersion on limb and cutaneous blood flow after exercise. Med Sci Sport Exerc. 2013;45:2277–85.
11. Gregson W, Black MA, Jones H, Milson J, Morton J, Dawson B, et al. Influence of cold water immersion on limb and cutaneous blood flow at rest. Am J Sports Med. 2011;39:1316–23.
12. Broatch JR, Petersen A, Bishop DJ. Postexercise cold water immersion benefits are not greater than the placebo effect. Med Sci Sports Exerc. 2014;46:2139–47.
13. de Malta ES, de Lira FS, Machado FA, Zago AS, do Amaral SL, Zagatto AM. Photobiomodulation by led does not alter muscle recovery indicators and presents similar outcomes to cold-water immersion and active recovery. Front Physiol Front. 2019;9:1948.
14. Ascensão A, Leite M, Rebelo AN, Magalhäes S, Magalhäes J. Effects of cold water immersion on the recovery of physical performance and muscle damage following a one-off soccer match. J Sports Sci. 2011;29:217–25.
15. Eston R, Peters D. Effects of cold water immersion on the symptoms of exercise-induced muscle damage. J Sports Sci. 1999;17:231–8.
16. Pournot H, Bieuzen F, Duffield R, Lepretre P-M, Cozzolino C, Hausswirth C. Short term effects of various water immersions on recovery from exhaustive intermittent exercise. Eur J Appl Physiol. 2011;111:1287–95.
17. Rowsell GJ, Coutts AJ, Reaburn P, Hill-Haas S. Effect of post-match cold-water immersion on subsequent match running performance in junior soccer players during tournament play. J Sports Sci. 2011;29:1–6.
18. Machado AF, Ferreira PH, Micheletti JK, de Almeida AC, Lemes ÍR, Vanderlei FM, et al. Can water temperature and immersion time influence the effect of cold water immersion on muscle soreness? A systematic review and meta-analysis. Sports Med. 2016;46:503–14.
19. Vaile J, Halson S, Gill N, Dawson B. Effect of hydrotherapy on the signs and symptoms of delayed onset muscle soreness. Eur J Appl Physiol. 2008;102:447–55.
20. Roberts LA, Nosaka K, Coombes JS, Peake JM. Cold water immersion enhances recovery of submaximal muscle function after resistance exercise. Am J Physiol Regul Integr Comp Physiol. 2014;307:R998-1008.
21. Aguiar PF, Magalhães SM, Fonseca IAT, Santos VB da C, Matos MA de, Peixoto MFD, et al. Post-exercise cold water immersion does not alter high intensity interval training-induced exercise performance and Hsp72 responses, but enhances mitochondrial markers. Cell Stress Chaperones 2016;21:793.
22. Ihsan M, Markworth JF, Watson G, Choo HC, Govus A, Pham T, et al. Regular postexercise cooling enhances mitochondrial biogenesis through AMPK and p38 MAPK in human skeletal muscle. Am J Physiol Integr Comp Physiol. 2015;309:R286–94.
23. Roberts LA, Raastad T, Markworth JF, Figueiredo VC, Egner IM, Shield A, et al. Post-exercise cold water immersion attenuates acute anabolic signalling and long-term adaptations in muscle to strength training. J Physiol. 2015;593:4285–301.
24. Fyfe JJ, Broatch JR, Trewin AJ, Hanson ED, Argus CK, Garnham AP, et al. Cold water immersion attenuates anabolic signalling and skeletal muscle fiber hypertrophy, but not strength gain, following whole-body resistance training. J Appl Physiol. 2019;127:1403–18.
25. Fuchs CJ, Kouw IWK, Churchward-Venne TA, Smeets JSJ, Senden JM, van Lichtenbelt WDM, et al. Postexercise cooling impairs muscle protein synthesis rates in recreational athletes. J Physiol. 2019;598:755–72.
26. de Matos MA, Vieira DV, Pinhal KC, Lopes JF, Dias-Peixoto MF, Pauli JR, et al. High-intensity interval training improves markers of oxidative metabolism in skeletal muscle of individuals with obesity and insulin resistance. Front Physiol. 2018;9:1451.
27. Halson SL, Bartram J, West N, Stephens J, Argus CK, Driller MW, et al. Does hydrotherapy help or hinder adaptation to training in competitive cyclists? Med Sci Sports Exerc. 2014;46:1631–9.
28. Yamane M, Teruya H, Nakano M, Ogai R, Ohnishi N, Kosaka M. Post-exercise leg and forearm flexor muscle cooling in humans attenuates endurance and resistance training effects on muscle performance and on circulatory adaptation. Eur J Appl Physiol. 2006;96:572–80.
29. Gamble P. Periodization of training for team sports athletes. Strength Cond J. 2006;28:56–66.
30. Issurin VB. New horizons for the methodology and physiology of training periodization. Sport Med. 2010;40:189–206.
31. Suchomel TJ, Nimphius S, Bellon CR, Stone MH. The importance of muscular strength: training considerations. Sport Med. 2018;48:765–85.
32. Versey NG, Halson SL, Dawson BT. Water immersion recovery for athletes: effect on exercise performance and practical recommendations. Sports Med. 2013;43:1101–30.
33. Broatch JR, Petersen A, Bishop DJ. The influence of post-exercise cold-water immersion on adaptive responses to exercise: a review of the literature. Sport Med. 2018;48:1369–87.
34. Harries SK, Lubans DR, Callister R. Systematic review and meta-analysis of linear and undulating periodized resistance training programs on muscular strength. J strength Cond Res. 2015;29:1113–25.

35. Higgins JP, Altman DG. Assessing risk of bias in included studies. Cochrane Handb Syst Rev Interv. Chichester: Wiley; 2018.
36. Yamane M, Ohnishi N, Matsumoto T. Does regular post-exercise cold application attenuate trained muscle adaptation? Int J Sports Med. 2015;36:647–53.
37. Grosshans E, Campbell H, Eddama O, Azzopardi D, Edwards AD, Strohm B, et al. Who should we cool after perinatal asphyxia? J Drugs Dermatol. 2014;26:59–67.
38. Jones EJ, Bishop PA, Woods AK, Green JM. Cross-sectional area and muscular strength: A brief review. Sport Med. 2008;38:987–94.
39. Kraemer WJ, Ratamess NA. Fundamentals of resistance training: progression and exercise prescription. Med Sci Sports Exerc. 2004;36:674–88.
40. Shima A, Matsuda R. The expression of myogenin, but not of MyoD, is temperature-sensitive in mouse skeletal muscle cells. Zoolog Sci. 2008;25:1066–74.
41. Fukunaga T, Miyatani M, Tachi M, Kouzaki M, Kawakami Y, Kanehisa H. Muscle volume is a major determinant of joint torque in humans. Acta Physiol Scand. 2001;172:249–55.
42. Buckner SL, Dankel SJ, Mattocks KT, Jessee MB, Mouser JG, Counts BR, et al. The problem of muscle hypertrophy: revisited. Muscle Nerve. 2016;54:1012–4.
43. Fujita S, Rasmussen BB, Cadenas JG, Grady JJ, Volpi E. Effect of insulin on human skeletal muscle protein synthesis is modulated by insulin-induced changes in muscle blood flow and amino acid availability. Am J Physiol Metab. 2006;291:E745–54.
44. Tipton KD, Wolfe RR. Exercise, protein metabolism, and muscle growth. Int J Sport Nutr. 2001;11:109–32.
45. Slattery KM, Wallace LK, Murphy AJ, Coutts AJ. Physiological determinants of three-kilometer running performance in experienced triathletes. J Strength Cond Res. 2006;20:47.
46. Jacobs RA, Rasmussen P, Siebenmann C, Díaz V, Gassmann M, Pesta D, et al. Determinants of time trial performance and maximal incremental exercise in highly trained endurance athletes. J Appl Physiol. 2011;111:1422–30.
47. Bassett DR, Howley ET. Limiting factors for maximum oxygen uptake and determinants of endurance performance. Med Sci Sports Exerc. 2000;32:70–84.
48. Lundby C, Jacobs RA. Adaptations of skeletal muscle mitochondria to exercise training. Exp Physiol. 2016;101:17–22.
49. Meinild-Lundby AK, Jacobs RA, Gehrig S, de Leur J, Hauser M, Bonne TC, et al. Exercise training increases skeletal muscle mitochondrial volume density by enlargement of existing mitochondria and not de novo biogenesis. Acta Physiol. 2018;2018:222.
50. Hawley JA, Lundby C, Cotter JD, Burke LM. Maximizing cellular adaptation to endurance exercise in skeletal muscle. Cell Metab. 2018;27:962–76.
51. MacInnis MJ, Gibala MJ. Physiological adaptations to interval training and the role of exercise intensity. J Physiol. 2017;595:2915–30.
52. Ihsan M, Watson G, Choo HC, Lewandowsk P, Papazzo A, Cameron-Smith D, et al. Postexercise muscle cooling enhances gene expression of PGC-1α. Med Sci Sport Exerc. 2014;46:1900–7.
53. Allan R, Sharples AP, Close GL, Drust B, Shepherd SO, Dutton J, et al. Postexercise cold water immersion modulates skeletal muscle PGC-1α mRNA expression in immersed and nonimmersed limbs: evidence of systemic regulation. J Appl Physiol. 2017;123:451–9.
54. Joo CH, Allan R, Drust B, Close GL, Jeong TS, Bartlett JD, et al. Passive and post-exercise cold-water immersion augments PGC-1α and VEGF expression in human skeletal muscle. Eur J Appl Physiol. 2016;116:2315–26.
55. Granata C, Jamnick NA, Bishop DJ. Training-induced changes in mitochondrial content and respiratory function in human skeletal muscle. Sport Med. 2018;48:1809–28.
56. Vogel C, Marcotte EM. Insights into the regulation of protein abundance from proteomic and transcriptomic analyses. Nat Rev Genet. 2012;13:227–32.
57. Foster C, Costill DL, Daniels JT, Fink WJ. Skeletal muscle enzyme activity, fiber composition and VO2 max in relation to distance running performance. Eur J Appl Physiol Occup Physiol. 1978;39:73–80.
58. Sutton JR. Limitations to maximal oxygen uptake. Sport Med An Int J Appl Med Sci Sport Exerc. 1992;13:127–33.
59. Siqueira AF, Vieira A, Bottaro M, Ferreira-Júnior JB, de Nóbrega OT, de Souza VC, et al. Multiple cold-water immersions attenuate muscle damage but not alter systemic inflammation and muscle function recovery: a parallel randomized controlled trial. Sci Rep. 2018;8:10961.
60. Abaïdia AE, Lamblin J, Delecroix B, Leduc C, McCall A, Nédélec M, et al. Recovery from exercise-induced muscle damage: cold-water immersion versus whole-body cryotherapy. Int J Sports Physiol Perform. 2017;12:402–9.
61. De Paula F, Escobar K, Ottone V, Aguiar P, de Matos MA, Duarte T, et al. Post-exercise cold-water immersion improves the performance in a subsequent 5-km running trial. Temperature. 2018;5:359–70.
62. Peake JM, Neubauer O, Della Gatta PA, Nosaka K. Muscle damage and inflammation during recovery from exercise. J Appl Physiol. 2017;122:559–70.
63. Pedersen BK, Hoffman-Goetz L. Exercise and the immune system: regulation, integration, and adaptation. Physiol Rev. 2000;80:1055–81.
64. Ritchie D, Hopkins WG, Buchheit M, Cordy J, Bartlett JD. Quantification of training and competition load across a season in an Elite Australian football club. Int J Sports Physiol Perform. 2016;11:474–9.
65. Tnønessen E, Sylta Ø, Haugen TA, Hem E, Svendsen IS, Seiler S. The road to gold: training and peaking characteristics in the year prior to a gold medal endurance performance. PLoS ONE. 2014;9:e101796.
66. Ihsan M, Abbiss CR, Gregson W, Allan R. Warming to the ice bath: Don't go cool on cold water immersion just yet! Temperature. 2020;2020:1–3.

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