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REVIEW

Cold Water Immersion, Heart Rate Variability and Post-Exercise Recovery: A Systematic Review

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ABSTRACT

Introduction: Physiological and psychological recovery, i.e., the balance between fatigue/stress and recovery and evaluated through heart rate variability (HRV), is essential for the good performance of athletes in all their activities. Cold water immersion (CWI) has been shown to reduce the negative effects of fatigue/stress by inducing physiological and biochemical changes that promote faster recovery. This study aims to analyze the scientific literature on the effects of CWI on post-exercise recovery, as measured by HRV in athletes.

Methods: A systematic review of randomized clinical trials (RCTs) was conducted following PRISMA guidelines. Databases such as Scopus, Web of Science, and MEDLINE were included it. The risk of bias of each study selected was assessed using Cochrane's guidelines for RCT.

Results: Twelve articles were included. All studies reported parasympathetic reactivation with CWI after physical exertion. Six studies demonstrated statistically significant results ($p < 0.05$) compared to a passive recovery, while eight studies reported moderate to large effect sizes.

Conclusion: The results of this study indicate that CWI after exercise may have a positive acute effect on parasympathetic reactivation, as measured by HRV.

1 | Introduction

Recovery is defined as the balance between stress/fatigue and the athlete's ability to perform, encompassing physiological and psychological responses that must be evaluated and monitored (Kellmann et al. 2018). Scientific evidence declared, that insufficient recovery can lead to overtraining, which increases the risk of injuries and hinders the athlete's ability to achieve optimal performance (Carrard et al. 2022). Given the critical importance of effective recovery strategies in sports training programs (Moore et al. 2022), cold water immersion (CWI) has gained attention for its physiological and biochemical effects. CWI aims to reduce the negative impact of training or competition and promote a faster return to peak performance (Petersen and Fyfe 2021).

The scientific literature validates CWI as a strategy for benefiting the recovery of athletes (Cullen, Casazza, and

Davis 2021; Moore et al. 2022; Petersen and Fyfe 2021). In this regard, some studies indicate that CWI does not affect the adaptations of aerobic training and can be incorporated as a recovery modality after resistance training. In addition, other authors indicate that CWI improves short-term performance and facilitates recovery during competition. Evidence also shows that the application of cold water could have a negative effect on the adaptations to strength training (Ihsan, Abbiss, and Allan 2021; Malta et al. 2021).

As a key tool in assessing recovery and monitoring athletic performance, Heart rate variability (HRV) has emerged as a non-invasive marker of autonomic nervous system activity due to its ease of use and the large number of devices that can measure it, which makes it a sports performance variable (Manresa-Rocamora et al. 2021; Marasingha-Arachchige et al. 2022). HRV reflects the balance between parasympathetic and sympathetic activity, making it a reliable indicator as a measure of post-exercise recovery (Liu et al. 2021; Hung et al. 2020), yet limited research has explored its application in assessing the effects of CWI.

This gap in the literature highlights the need for further investigation into how CWI influences post-exercise recovery as measured by HRV. Therefore, this study aims to analyze the scientific literature about the effect of CWI on post-exercise recovery measured by HRV in athletes.

2 | Methods

2.1 | Design and Protocol

In this article, a systematic review of randomized clinical trials (RCT) was conducted based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standard (Page et al. 2021).

2.2 | Search Strategy

A search was conducted on the following databases: Scopus, Web of Science (WOS) and MEDLINE (through PubMed). The search terms used were obtained from the MeSH terms and are "Exercise", "Sports", "Hydrotherapy", "Cryotherapy", "Immientes" free text terms, "Post exercise", After exercise", "Exercise response", "Post training", "Cold water immersion", "Water immersion", "Cooling strategies", "Cooling", "Heart rate variability", "Autonomic function", "Cardiac autonomic control", "Autonomic cardiovascular control", "Vagal modulation", "Vagal tone", and "Parasympathetic activity".

To execute the search on the MEDLINE database, the sensitive search strategy proposed in Cochrane's Handbook was employed. This strategy consists of combining all the above-mentioned terms, MeSH (PubMed Thesaurus) and free text, with the Boolean terms AND and OR.

1. "Exercise" (MeSH)
2. "Sports" (MeSH)
3. Post exercise.
4. After exercise.
5. Exercise response.
6. Post training.
7. #1 OR #2 OR #3 OR #4 OR #5 OR #6
8. "Hydrotherapy" (MeSH)
9. "Cryotherapy" (MeSH)
10. "Immersion" (MeSH)
11. "Cold" (MeSH)
12. Cold water immersion.
13. Water immersion.
14. Cooling strategies.
15. Cooling.
16. #8 OR #9 OR #10 OR #11 OR #12 OR #13 OR #14 OR #15
17. "Autonomic nervous system" (MeSH)
18. Heart rate variability.
19. Autonomic function.
20. Cardiac autonomic control.
21. Autonomic cardiovascular control.
22. Vagal modulation.
23. Vagal tone.
24. Parasympathetic activity.
25. #17 OR #18 OR #19 OR #20 OR #21 OR #22 OR #23 OR #24
26. #7 AND #16 AND #25
27. Lastly, the filter "randomized clinical trials" was applied.

For the other databases, Scopus and WOS, the same terms were employed, and the search strategy was to combine the terms in the advanced search option. In addition, a search chain was conducted independently, reviewing the references of the articles identified.

2.3 | Eligibility Criteria

The selection of articles incorporated and then analyzed, the following criteria were considered: RCT and crossover design studies because they represent the gold standard for minimizing bias and establishing causal relationships, no language restrictions, articles published up to January 2023 incorporating the most up-to-date evidence available, no restrictions age, gender or race restriction so that be understood across diverse populations without demographic limitations, and studies incorporating CWI post-exercise where the intervention is widely used in athletic recovery protocols and is of particular interest for its effects on HRV.

2.4 | Selection Criteria

Inclusion criteria: These criteria were established based on the PICOT guidelines (population, intervention, comparison, outcomes, and design of the study) as follows:

Population: Studies that include elite athletes, amateur athletes or physically active people, ages 18+, men, women or of both sexes.

Intervention: Studies that incorporate CWI ≤ 15°C after exercise.

Comparison: Studies that incorporate a control group.

Outcomes: Studies that evaluate heart rate variability after the intervention with CWI post exercise.

Type of design: Randomized clinical trials and crossover trials.

RCTs that include interventions in humans.

2.5 | Exclusion Criteria

Studies that used head immersion or isolated immersion of one body part; (e.g., a foot, face, or arm) were excluded because of the different physiological responses that occur with full-body immersion and the heterogeneous responses that can arise from each body segment. Similarly, articles that used combined treatments (e.g., combining CWI with compression garments, combining CWI with AR, combining CWI with nutritional supplements) were excluded because these interventions amplify, diminish, or modify the results, creating confusion regarding the specific effects of CWI.

2.6 | Selection of Studies and Data Extraction

The study selection and data extraction processes will be conducted by two evaluators separately (CG, PV), who will fill in a standardized form to collect the information. In case of disagreement or discrepancy, the authors agreed to submit it to an independent consultant (AE) for analysis, to then decide its final inclusion through discussion and consensus. The following information was extracted from the studies included: characteristics of the study (i.e., year of publication, design of the study, country, and sample size), characteristics of the participants (sport, sex, age, body mass, body mass index, height, maximal oxygen intake), characteristics of the exercise previous to the intervention (type and dose of exercise or training prior to CWI and/or recovery method), characteristic of the intervention (dose of the cold water intervention post exercise), characteristics of the control and/or placebo group (type and doses of comparison intervention), characteristics of the HRV assessment (conditions under which HRV was assessed: duration of the record, posture, respiratory rate), and result measures (measures associated with HRV "RR interval (ms), RMSSD (ms), SDNN (ms), pNN50 (%), TP (ms2), VLF (ms2), LF (ms2), HF (ms2) and LF/HF, as well as non-linear measures such as S (ms), SD1 (ms), SD2 (ms), SD1/SD2 (%), ApEn, SampEn, DFA α1, DFA α2, D_2, with their respective measurement times").

2.7 | Evaluation of Risk of Bias

The risk of bias of each study was assessed quantitatively and the results of each study are shown in a classification table. The risk of bias of the studies was evaluated using the tool proposed in the Cochrane's Handbook for randomized clinical trials. The domains assessed in the studies are 7:

1. Generation of the randomization sequence.
2. Allocation concealment.
3. Participant blinding.
4. Assessor blinding.
5. Incomplete outcome data.
6. Selective notification of results and
7. Other sources of bias.

3 | Results

3.1 | Selection of Studies

Based on the eligibility criteria of this review, in the preliminary search, 146 articles were identified in the MEDLINE, Scopus and WOS databases, and 6 articles were found based on citation search. Twenty-eight potentially eligible studies were selected, but only 12 were left for review after applying the inclusion criteria. This process is summarized in the flow diagram below (Figure 1).

3.2 | Characteristics of the Studies

The total sample size of this review was 240 individuals. The study with the most subjects included 100 participants (Almeida et al. 2016), while the study with the least included only 8 individuals (De Oliveira Ottone et al. 2014). The average number of subjects per study was 20, and the mean age of the sample in the studies was 23.38 years. All these data are summarized in Table 1.

When establishing a comparison, the 12 studies included in the review used the same intervention (Al Haddad, Parouty, and Buchheit 2012; Almeida et al. 2016; Bastos et al. 2012; Choo et al. 2018; De Oliveira Ottone et al. 2014; Douglas et al. 2016; Parouty et al. 2010; Ravier et al. 2022; Roberts et al. 2015; Stanley, Buchheit, and Peake 2012, 2013b, 2014), which corresponds to CWI, i.e., the subjects under study immerse part of their body. The dosing of the intervention is summarized in Table 1 and represented in Figure 2.

The main result measure associated with the time domain of HRV used in the articles included was rMSSD or its possible natural logarithm in all studies covered by the review (Bastos et al. 2012; Stanley, Buchheit, and Peake 2012; Stanley, Peake,

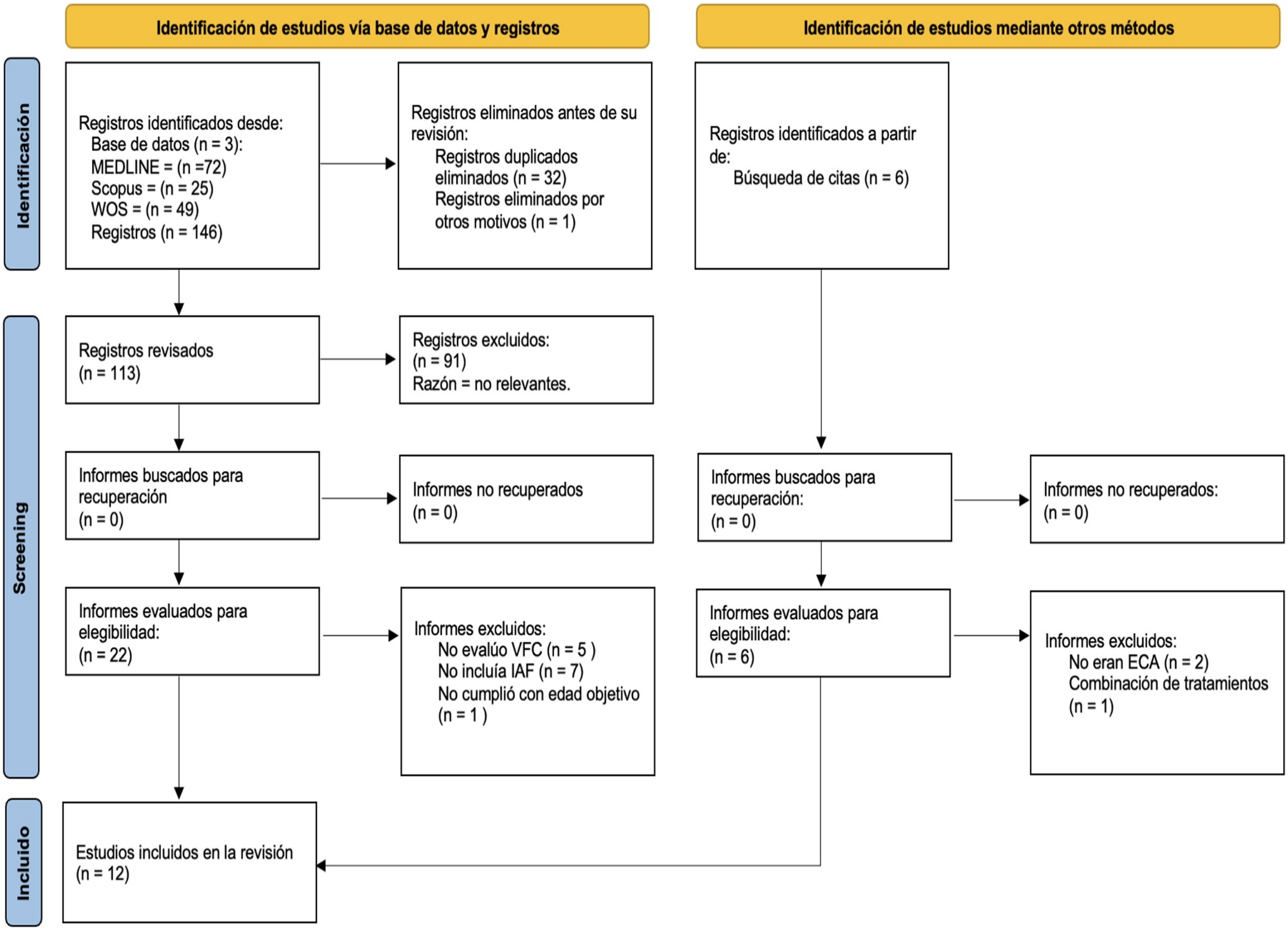

FIGURE 1 | Flow chart.

and Buchheit 2013b; Stanley et al. 2014; Parouty et al. 2010; Almeida et al. 2016; Al Haddad, Parouty, and Buchheit 2012; Douglas et al. 2016; Ravier et al. 2022; Choo et al. 2018; De Oliveira Ottone et al. 2014; Roberts et al. 2015). The studies that analyzed the other variables associated with the time domain and Poincaré quantitative analyses are described in Table 1.

3.3 | Individual Results

The results of each included study are summarized in Table 1.

3.4 | Risk of Bias Results

The risk of bias of the studies included in this review is presented in (Figure 3).

4 | Results Synthesis

The most surprising aspect of the general results of these studies is that the post-exercise CWI intervention could generate a positive acute effect in parasympathetic reactivation measured using HRV.

The effects observed in the athlete groups, their level of experience, and the type of sport highlight significant differences. Elite cyclists show a faster recovery in HRV than recreational athletes (Stanley, Buchheit, and Peake 2012; Stanley et al. 2014). Regarding team sport athletes such as those in football, handball, and rugby, Douglas et al. (2016) reported significant improvements in rMSSD after CWI sessions, with large and sustained effects compared to passive recovery (PR) methods. In the case of football and handball (Bastos et al. 2012; Ravier et al. 2022), the effects of CWI were also positive, with increases in HRV indices and greater recovery of autonomic markers compared with controls. On the other hand, in less trained or physically active athletes, positive effects of CWI are observed with longer durations required to reach comparable levels of recovery (Roberts et al. 2015; Choo et al. 2018; Al Haddad, Parouty, and Buchheit 2012; Almeida et al. 2016; Parouty et al. 2010).

5 | Discussion

The objective of this study was to analyze the scientific literature on post-exercise CWI for recovery measured using HRV in athletes or physically active people. Specifically, this article seeks to determine whether the effects of post-exercise CWI favor parasympathetic reactivation according to the HRV

TABLE 1 | Characteristics of the included studies.

Study/Type of RCT/Country	Characteristics of participants	Exercise prior to intervention	Intervention	HRV recording	Result measures	Results	Effect size/Significance
Bastos et al. 2012/ Cross-over/Brazil	Men Team sports: (soccer, basketball, handball) *N*: 20 Age: 21 ± 2 years. Body mass: 72 ± 11 kg. Height: 175 ± 8 cm. VO2max: 47.1 ± 3.1 mL kg^{-1} min^{-1}.	Extensive tests at constant speed on a treadmill	CWI: TIME: 6′ °C: 11 ± 2 IL: AIIS PG: AR, 6′ CG: PR, 6′	Recording position: Supine (I) Recording time: 3′RR: Spontaneous	rMSSD SDNN LF HF LF/HF	↑ SDNN in CWI versus PR at 15 min of recovery ($p < 0.05$). ↑ SDNN in CWI versus AR during the application of the recovery technique, 30 and 75 min post exercise ($p < 0.05$). rMSSD, moderate ES (+) in CWI versus PR, during the recovery technique (ES: 0.74), 15 min post exercise (ES: 0.69), and 30 min post exercise (ES: 0.57). ↑ Ln LF in CWI versus AR during the application of the recovery technique and 75 min post exercise ($p < 0.05$). Ln HF, large ES (−) in AR versus CWI, during the recovery technique (ES: −1.09). Ln HF, moderate ES (−) in PR versus CWI, during the recovery technique (ES: −0.58), and 15 min post exercise (ES: −0.64). LF/HF, moderate S (+) in AR versus CWI, at 15 min post exercise (ES: 0.66), and large ES at 60 min post exercise (ES: 0.84). LF/HF, moderate ES (+) in PR versus CWI at 15 min post exercise (ES: 0.64), and at 60 min post exercise (ES: 0.51).	AR and CWI moderate to large effect sizes in HRV compared to PR CWI resulted in significantly higher values of SDNN and LnLF during and after the intervention, compared to AR and PR ($p < 0.05$).

(Continues)

TABLE 1 | (Continued)

Study/Type of RCT/Country	Characteristics of participants	Exercise prior to intervention	Intervention	HRV recording	Result measures	Results	Effect size/Significance
Stanley, Buchheit, and Peake 2012/ Cross-over/Australia	Men Cyclists *N*: 18 Age: 27 ± 7 years. Body Mass: 75.2 ± 9.0 kg. Height: 182 ± 6 cm. VO2max: 63.9 ± 7.2 mL kg^{-1} min^{-1}.	HIIT in cycle ergometer	CWI: Time: 5′ °C: 14.2 ± 0.6 IL: Shoulders PG: COWI, 10′ CG: PR, 10′	Recording position: Supino (I) Recording time: 5′ RR: Spontaneous	rMSSD	The change in the rMSSD mean after the recovery intervention was almost certainly higher post CWI (16% [10.4; 23.2]) and very likely higher post COWI (12.5% [5.5; 20.0]) versus PR, and possibly higher post CWI (3.7% [−0.9; 8.4]) versus COWI.	CWI with a large effect size (1.10), being “almost certainly larger” while CWI compared to COWI with a small effect size (0.26), being “possibly larger”. Significant values on post-recovery rMSSD
Parouty et al. 2010/ Cross-over/France	Men (*N*: 5) Women (*N*: 5) Swimmers *N*: 10 Age: 19.0 ± 3.9 years.	100 M swimming sprint	CWI: Time: 5′ °C: 14–15 IL: Shoulders CG: PR, 5′	Recording position: Seated (PR) Recording time: 5′ RR: Spontaneous	rMSSD	CWI was associated with a “likely” lower decrease in rMSSD (4.1, 30.9). rMSSD after maximum sprint No.2 (S2) showed higher values in CWI versus PR (3, 0.19 ± 0.57 vs. 2.85 ± 1.10), with a probability of true numbers being lower/trivial/ superior to 2/21/77%).	CWI in rMSSD (−16.7% ES), with a standardized difference considered “moderate”.
Almeida et al. 2016/ Parallel/Brazil	Men Physically active *N*: 100 Age: 21.73 ± 2.92 years. Body Mass: 74.22 ± 10.15 kg. Height: 175 ± 6 cm.	Jump protocol and Wingate test	CWI: G1 Time: 5′ °C: 9 ± 1 G2 Time: 5′ °C: 14 ± 1 G3 Time: 15′ °C: 9 ± 1 G4 Time: 15′ °C: 14 ± 1 IL: AIIS CG: PR, 15′	Recording position: Seated (PR) Recording time: 5′ RR: Spontaneous	rMSSD mRR SDNN VLF LF HF SD1 SD2	In mRR, VLF and LF, an earlier recovery was observed between 10 and 20 min in the CWI groups versus PR groups. For SDNN and SD2, G4 presented an earlier recovery (10 min) versus the other groups. For rMSSD, HF and SD1, there were no differences in recovery time for any group.	CWI resulted in significantly values of recovery ($p < 0.05$). In the groups comparison, G4 presented statistically greater ($p < 0.05$) results compared to CG. Between time and intervention, a significant interaction for mean RR ($p < 0.001$), SDNN ($p = 0.001$), RMSSD ($p = 0.003$), VLF ($p = 0.025$), SD1 ($p = 0.014$) and SD2 ($p = 0.045$).

(Continues)

TABLE 1 | (Continued)

Study/Type of RCT/Country	Characteristics of participants	Exercise prior to intervention	Intervention	HRV recording	Result measures	Results	Effect size/Significance
Al Haddad, Parouty, and Buchheit 2012/ Cross-over/France	Men Physically active *N*: 12 Age: 21.6 ± 1.4 years. Body Mass: 76.5 ± 12.2 kg. Height: 1.80 ± 0.05 cm.	Intermittent exercise (Wingate test and submaximal sprinting exercise)	CWI: Time: 5′ °C: 14–15 IL: not mentioned PG: TNWI, 5′ CG: PR, 5′	Recording position:not mentioned Recording time: 3′ RR: Spontaneous	rMSSD mRR SD1 SD2 SD1/SD2	↑ rMSSD was > with CWI (2.32 ± 0.67 ms) versus PR (1.98 ± 0.74 ms) and TNWI (2.01 ± 0.61 ms), and ↔ between PR versus TNWI. ↔ SD1, SD2, SD1/SD2 in the 3 conditions ($p = 0.19$). ↑ rMSSD increases faster in TNWI (60 s; $p = < 0.001$), and in CWI (90 s; $p = 0.008$), versus PR (180 s; $p = 0.026$). ↑ rMSSD higher at 300 s ($P = 0.044$) for the CWI condition versus TNWI.	rMSSD resulted in significantly higher values with CWI ($p = 0.05$) and TNWI ($p = 0.08$) ES = 1.07. mRR was > in CWI versus PR (ES: 0.58), and versus TNWI (ES: 0.89). ↑ mRR was > in CWI versus TNWI (ES: 0.61).
Douglas et al. 2016/ Cross-over/ New Zealand	Men Team sports: (Rugby seven) *N*: 10 Age: 25 ± 3 years. Body Mass: 88 ± 9 kg. Height: 181 ± 4 cm. VO2max: 56.3 ± 5.8 mL kg^{-1} min^{-1}.	Simulation of rugby seven game (exercise in arm ergometer and a cone guided race)	CWI: Time: 5′ °C: 14 IL: Neck CG: PR, 5′	Recording position: Seated (PR) Recording time: 3′ RR: Spontaneous	rMSSD	CWI induced a clear cardiac parasympathetic reactivation, with postintervention rMSSD being most likely moderately higher than PAS after all matches	rMSSD, large ES (+) in CWI and was moderately superior to PR after all games (ES: 90%). No differences were observed for pre-warm-up, during profiling or match 1.

(Continues)

TABLE 1 | (Continued)

Study/Type of RCT/Country	Characteristics of participants	Exercise prior to intervention	Intervention	HRV recording	Result measures	Results	Effect size/Significance
Ravier et al. 2022/ Cross-over/France	Women Team sports: Handball *N*: 18 Age: 18.8 ± 0.4 years. Body Mass: 72.9 ± 10 kg. Height: 177.2 ± 7.5 cm.	Handball training session	CWI: Time: 6′ °C: 10 ± 0,5 IL: bellybutton PG:G1: COWI, 8′ G2: COWI, 10′ CG: G3: PR, 6′ G4: PR, 8′ G5: PR, 10′	Recording position: Seated (PR) Recording time: 5′ RR: Spontaneous	rMSSD mRR SDNN LF HF SD1 SD2	All parasympathetic indexes showed higher post-recovery values in CWI than in CG ($p < 0.001$, with big ES from 0.86 to 0.94). ↔ between COWI, 8′ and COWI, 10′versus. CG, except for COWI, 8′in Ln SD1, (p: 0.049). Post-training vs post-recovery values: ↑ parasympathetic indexes in the 3 modalities (CWI, PG, CG). Post-training vs post-recovery values: CWI and PG at 60 min exhibited higher post-exercise values than pre-training values in parasympathetic HRV indexes.	For the CWI + PAS modality, the difference between pre- and post-training was significant ($p < 0.001$, moderate to large ES) with a decrease in lnRMSSD, lnHF, RR, SDNN, lnSD1 and SD2 indices. rMSSD, big ES in CWI and PG (1.69–2.11), large ES but smaller than in CG (0.89 and 1.67).
Choo et al. 2018/ Cross-over/Australia	Men *N*: 9 Age: 29 ± 9 years Body Mass: 72.7 ± 6.6 kg. Height: 172 ± 5 cm. VO2max: 40.4 ± 3.6 mL kg^{-1} min^{-1}.	Series exercises at 90% maximum power in the cycle ergometer.	CWI: G1: Time: 5′ °C: 8.6 ± 0.2 G2: Time: 5′ °C: 14.6 ± 0.3 IL: Sternum PG: TNWI, 5′ CG: PR, 5′	Recording position: Seated (PR) Recording time: 3′ RR: Spontaneous	rMSSD LF HF SD1 SD2 SD1/SD2	CWI and PG reestablished the HRV indexes (rMSSD, LF, HF, SD1, SD1) at 60 min post immersion. Only CWI (G1) accelerated the parasympathetic reactivation during the recovery technique. ↑ LF and SD2 during CWI (G1) versus CG ($p < 0.05$).	CWI (G1), large ES (+) (ES: > 0.80) in all the HRV indexes during the recovery technique versus CG, only significant differences (↑) in LF and SD2 ($p = 0.017$–0.023). CWI (G2), large ES rMSSD and SD1 versus CG (ES: > 0.80), but without a significant difference (p: 0.064).

(Continues)

TABLE 1 | (Continued)

Study/Type of RCT/Country	Characteristics of participants	Exercise prior to intervention	Intervention	HRV recording	Result measures	Results	Effect size/Significance
De Oliveira Ottone et al. 2014/Cross-over/Brazil	Men Team sports: (soccer), individual sports: (cycling, running). *N*: 8 Age: 24 ± 6 years. Body Mass: 68 ± 8.6 kg. Height: 176 ± 3.3 cm. VO2max: 54.2 ± 3.6 mL kg^{-1} min^{-1}.	Eccentric strength exercise of unilateral knee flexion + submaximal aerobic exercise.	CWI: Time: 15′ °C: 15 ± 1 IL: xyphoid process PG: G1: WWI, 15′ G2: HWI, 15′ CG: PR, 15′	Recording position: Seated (PR) Recording time: 5′ RR: not mentioned	rMSSD mRR SD1 SD	HRV during recovery technique: mRR, during the recovery technique (CWI) did not differ from the pre-exercise measurement but decreased in CG and PG. rMSSD and SD1, lower values for PG versus pre-exercise measurement. HRV 30 min post-recovery intervention: mRR, rMSSD and Ln SD1 decreased for HWI versus pre-exercise measurement HRV 4 h post-exercise: HWI, showed a ↓ mRR versus pre-exercise measurement (*p*: 0,0042). ↔ in all other conditions.	There were no significant differences in the HRV indices measured at REST or during exercise in CWI. HRV 30 min post-recovery intervention there was significant differences ↑ mRR for CWI versus CG ($p = 0.0052$). CWI, large ES for all the HRV indexes (rMSSD, mRR, SD1, SD2)
Stanley, Peake, and Buchheit 2013b/ Cross-over/Australia	Men Cyclists *N*: 11 Age: 27 ± 6 years. Body Mass: 73.4 ± 8.2 kg. Height: 1.76 ± 0,06 cm. VO2max: 64.8 ± 6.0 mL kg^{-1} min^{-1}.	Maximal effort sprints and cycle ergometer against time	CWI: Time: 5′ °C: 10.1 ± 0.8 IL: Shoulders CG: PR, 5′	Recording position: Seated (PR) Recording time: 3′ RR: Spontaneous	rMSSD	HRV post recovery intervention:rMSSD immediately after the intervention technique was higher in CWI versus CG (+114% [92; 211]) on day 1. rMSSD, % of possibilities that CWI values are superior/trivial/inferior to CG (100/0/0), classifying the difference as "almost safe" on day 1.	rMSSD, large ES (+) (ES: 1.2) in CWI versus CG on day 1.
					rMSSD		

(Continues)

TABLE 1 | (Continued)

Study/Type of RCT/Country	Characteristics of participants	Exercise prior to intervention	Intervention	HRV recording	Result measures	Results	Effect size/Significance
Stanley et al. 2014/ Cross-over/Australia	Men Cyclists *N*: 14 Age: 25 ± 4 years. Body Mass: 69.6 ± 4.9 kg. Height: 177 ± 4 cm. VO2max: 66.6 ± 4.2 mL kg^{-1} min^{-1}.	2 series of HIIT in cycle ergometer	CWI: Time: 5′ °C: 10.1 ± 0.1 IL: bellybutton CG: PR, 5′	Recording position: Seated (PR) Recording time: 3′ RR: Spontaneous		rMSSD was likely higher [differences between trials (CI of 90%) (3.3; 24.0) after CWI versus CG before HIIT 2].	rMSSD shows a relevant ES between tests (CWI) with a difference of +13.2%.
Roberts et al. 2015/ Cross-over/Australia	Men Physically active *N*: 10 Age: 21.4 ± 2.0 years. Body Mass: 83.7 ± 14.8 kg. Height: 180 ± 10 cm.	Strength exercise: maximal isokinetic knee extensions	CWI: Time: 10′ °C: 10.0 ± 0.2 IL: bellybutton CG: AR, 10′	Recording position: Seated (PR) Recording time: 5′ RR: Spontaneous	rMSSD	↑ rMSSD rapidly returned to the pre-exercise value during CWI, while ↓ rMSSD, remaining at the pre-exercise value 5 min after the recovery intervention in CG.	↑ rMSSD to the pre-exercise value during CWI, with statistically significant differences $p < 0.05$ and a large ES (ES: 1.8).

Abbreviations: (−): negative; (+), positive; ↑, significant difference in favor or increase; ↓, statistically significant difference against or decrease; ↔, without statistical difference; °C, temperature; AIIS, anterior inferior iliac Spine; AR, active recovery; CG, control group; COWI, contrast water immersion; CWI, cold water immersion; ES, effect size; G1, group 1; G2, group 2; G3, group 3; G4, group 4; G5, group 5; HF, high frequency (0.15–0,4 Hz); HIIT, high intensity interval training; HRV, heart rate variability; HWI, hot water immersion; IL, water immersion level; LF/HF, low and high frequency ratio; LF, low frequency (0.04–0,15 Hz); mRR, medium RR intervals; N, number of subjects; PG, placebo group; PR, passive recovery; rMSSD, root mean square of the differences between adjacent normal R-R intervals; RR, respiratory rate; SD1/SD2, autonomic interaction derived from Poincaré or the SD ratio; SD1, dispersion of points perpendicular to identity line of the Poincaré graph; SD2, dispersion of points along the identity line of the Poincaré graph; SDNN, standard deviation of the NN (R-R) intervals; TNWI, thermoneutral water immersion; VLF, very low frequency (0.00–0.04 Hz); VO2max, maximal oxygen uptake; WWI, warm water immersion.

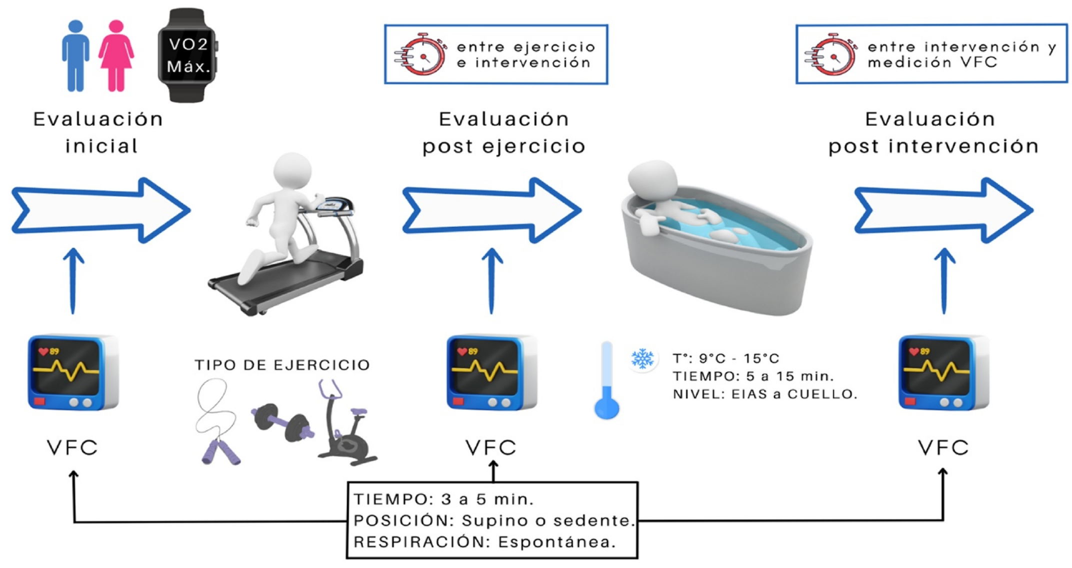

FIGURE 2 | Protocol and general characteristics of the studies included in the review.

analyses of the subjects included in the studies, and whether these effects are short-, medium-, or long term in the studied subjects, as well as to establish the most effective dose of cold-water immersion after exercise.

5.1 | HRV

The HRV recording and analysis protocols were similar across studies, with two recording durations observed: 4 min (Bastos et al. 2012; Al Haddad, Parouty, and Buchheit 2012; Douglas et al. 2016; Choo et al. 2018; Stanley, Peake, and Buchheit 2013b; Stanley et al. 2014) and 5 min (Stanley, Buchheit, and Peake 2012; Parouty et al. 2010; Almeida et al. 2016; Ravier et al. 2022; De Oliveira Ottone et al. 2014; Roberts et al. 2015). Some HRV variables calculated from less than 5 min of R-R intervals matched those from 5-min intervals, suggesting that ultra-short-term HRV could be a good alternative for evaluating HRV trends (Baek et al. 2015).

The recording positions for pre- and post-intervention were seated or supine, under controlled conditions. Position can be a key factor, as rMSSD can be significantly higher in the supine position compared with standing (Aubert, Seps, and Beckers 2003; Hnatkova et al. 2019). Only the study by Al Haddad, Parouty, and Buchheit (2012) did not specify the spontaneous respiratory rate in the methodology (Table 1). The equipment used for capturing R-R intervals included the "Polar S810i" (Bastos et al. 2012; Parouty et al. 2010; Al Haddad, Parouty, and Buchheit 2012; Choo et al. 2018), "Polar RS800CX" (Almeida et al. 2016; Douglas et al. 2016; De Oliveira Ottone et al. 2014), Suunto t6c (Stanley, Buchheit, and Peake 2012; Stanley, Peake, and Buchheit 2013b; Stanley et al. 2014; Roberts et al. 2015), and the HR1 chest belt, Matsport (Ravier et al. 2022), all of which have been validated in various studies (Gamelin, Berthoin, and Bosquet 2006; Weippert et al. 2010).

Studies have reported using specific software compatible with the signal capturing equipment (Bastos et al. 2012; Stanley, Buchheit, and Peake 2012; Stanley, Peake, and Buchheit 2013b; Stanley et al. 2014; Parouty et al. 2010; Almeida et al. 2016; Al Haddad, Parouty, and Buchheit 2012; Ravier et al. 2022; Choo et al. 2018; De Oliveira Ottone et al. 2014; Roberts et al. 2015). Data were then analyzed with "Kubios," specialized software validated for HRV assessment (Lipponen and Tarvainen 2019; Tarvainen et al. 2014; Bastos et al. 2012; Stanley, Buchheit, and Peake 2012; Stanley, Peake, and Buchheit 2013b; Stanley et al. 2014; Almeida et al. 2016; Douglas et al. 2016; Ravier et al. 2022; Choo et al. 2018; De Oliveira Ottone et al. 2014). Additionally, studies (Bastos et al. 2012; Parouty et al. 2010; Almeida et al. 2016; Al Haddad, Parouty, and Buchheit 2012; Douglas et al. 2016; Ravier et al. 2022; Choo et al. 2018; Stanley, Peake, and Buchheit 2013b; Stanley et al. 2014) reported correcting erratic data, eliminating artifacts, ectopic, and/or premature beats for improved analysis (Shaffer and Ginsberg 2017).

A relevant point of analysis is the variation in time at the end of the CWI intervention and the first HRV record. Five studies measured this variable during the intervention (Bastos et al. 2012; Almeida et al. 2016; Al Haddad, Parouty, and Buchheit 2012; Choo et al. 2018; De Oliveira Ottone et al. 2014). Three studies measured it after CWI (Ravier et al. 2022; Stanley, Peake, and Buchheit 2013b; Roberts et al. 2015), one study 1 min after CWI (Douglas et al. 2016), two studies 5 min after (Stanley, Buchheit, and Peake 2012; Parouty et al. 2010), and one approximately 10 min after (Stanley et al. 2014).

Regarding follow-up, Bastos et al. (2012) assessed HRV at 8, 23, 38, 53, 68, and 83 min post-intervention; Almeida et al. (2016) at 5, 15, 25, 35, and 45 min; Choo et al. (2018) at 30 and 60 min; De Oliveira Ottone et al. (2014) at 25 and 205 min; Stanley, Buchheit, and Peake (2012) at 10, 30, 60, 90, and 150 min; Douglas et al. (2016) at 120 min; Roberts et al. (2015) at 20 and 40 min; and Parouty et al. (2010) at 30 min after a second swimming sprint. Stanley et al. (2014) followed up 50 min after HIIT. Three studies did not report same-day follow-up (Al Haddad, Parouty, and Buchheit 2012; Ravier et al. 2022; Stanley, Peake, and Buchheit 2013b), but Stanley, Peake, and Buchheit (2013b) conducted the intervention

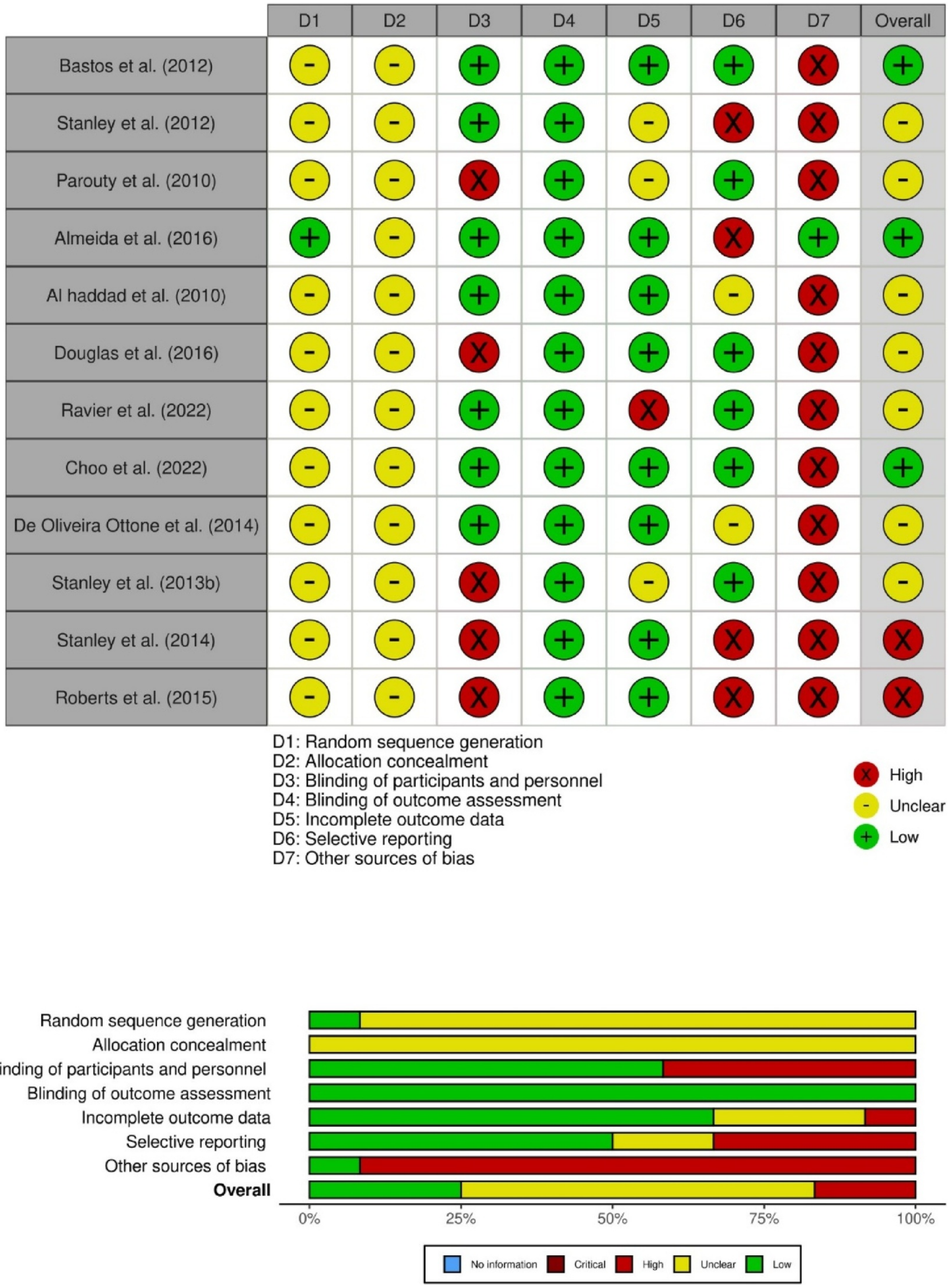

FIGURE 3 | Risk-of-bias results.

for 3 consecutive days, measuring HRV during sleep and upon waking. Douglas et al. (2016) evaluated this measure in 6 different games over 2 days, and Ravier et al. (2022) assessed HRV on 6 different handball training days.

5.2 | Result Measures and Their Interpretation

5.2.1 | Time Domain

Data from different researchers are comparable in the time domain only if collected under the same conditions and time periods (Mccraty and Shaffer 2015). This review includes studies that measured HRV for 3 min (Bastos et al. 2012; Al Haddad, Parouty, and Buchheit 2012; Douglas et al. 2016; Choo et al. 2018; Stanley, Peake, and Buchheit 2013b; Stanley et al. 2014) or 5 min (Stanley, Buchheit, and Peake 2012; Parouty et al. 2010; Almeida et al. 2016; Ravier et al. 2022; De Oliveira Ottone et al. 2014; Roberts et al. 2015), making comparisons challenging.

Regarding variables, mRR was evaluated in four studies (Almeida et al. 2016; Al Haddad, Parouty, and Buchheit 2012; Ravier et al. 2022; De Oliveira Ottone et al. 2014), all of which reported reductions with CWI treatment, although not the lowest vaues compared to other immersion treatments (De

Oliveira Ottone et al. 2014). All studies measured rMSSD or its natural logarithm (Bastos et al. 2012; Stanley, Buchheit, and Peake 2012; Stanley, Peake, and Buchheit 2013b; Stanley et al. 2014; Parouty et al. 2010; Almeida et al. 2016; Al Haddad, Parouty, and Buchheit 2012; Douglas et al. 2016; Ravier et al. 2022; Choo et al. 2018; De Oliveira Ottone et al. 2014; Roberts et al. 2015). rMSSD reflects beat-to-beat HR variance and is a key measure for vagally mediated HRV changes (Mccraty and Shaffer 2015) and is preferred for athletic populations (Flatt, Hornikel, and Esco 2017; Plews et al. 2013; Sherman et al. 2021). It is also minimally affected by respiratory rate (Penttilä et al. 2001; Shaffer and Ginsberg 2017).

SDNN was assessed in only three studies (Bastos et al. 2012; Almeida et al. 2016; Ravier et al. 2022). In short-term recordings, SDNN variation is mainly mediated by the parasympathetic system, especially during slow and deep breathing (Mccraty and Shaffer 2015). The spontaneous respiratory rate in most studies, except (Al Haddad, Parouty, and Buchheit 2012), may affect SDNN results. SDNN values depend significantly on recording length, making comparisons between different durations problematic (Aubert, Seps, and Beckers 2003). Thus, results from Bastos et al. (2012) with a 3-min protocol cannot be compared to those from Almeida et al. (2016), Ravier et al. (2022) with 5-min records.

5.2.2 | Frequency Domain

All studies in this review, except for Al Haddad, Parouty, and Buchheit (2012), report that respiratory rate is spontaneous and uncontrolled, which is relevant for measuring HF, reflecting parasympathetic or vagal activity (Aubert, Seps, and Beckers 2003; Mccraty and Shaffer 2015). Four studies (Bastos et al. 2012; Almeida et al. 2016; Ravier et al. 2022; Choo et al. 2018) incorporated this variable, possibly affecting the parameter. Low HF is linked to stress, panic, anxiety, and worry, affecting psychological regulation (Mccraty and Shaffer 2015). LF reflects baroreceptor activity and was evaluated in four studies (Bastos et al. 2012; Almeida et al. 2016; Ravier et al. 2022; Choo et al. 2018). LF is influenced during slow breathing, generating cardiac oscillations in the LF band (Mccraty and Shaffer 2015). VLF is related to thermoregulation (Aubert, Seps, and Beckers 2003) and was measured in one study (Almeida et al. 2016), although a longer period is needed for a complete assessment (Aubert, Seps, and Beckers 2003; Mccraty and Shaffer 2015). One study (Bastos et al. 2012) measured the LF/HF ratio, but the reviewed evidence confirms that it does not precisely quantify the "sympathetic-vagal balance," nor health or disease (Billman 2013; Mccraty and Shaffer 2015; Shaffer and Ginsberg 2017).

5.2.3 | Poincaré Quantitative Analysis

SD1 and SD2 were analyzed in five studies (Almeida et al. 2016; Al Haddad, Parouty, and Buchheit 2012; Ravier et al. 2022; Choo et al. 2018; De Oliveira Ottone et al. 2014). SD1 measures short-term HRV in ms and is correlated with baroreflex sensitivity. RMSSD is identical to the non-linear parameter SD1 (Shaffer and Ginsberg 2017). SD2 measures HRV in the short and long term in ms and is correlated with LF power and baroreflex sensitivity (Shaffer and Ginsberg 2017). The SD1/SD2 ratio was used as an outcome measure in two studies (Al Haddad, Parouty, and Buchheit 2012; Choo et al. 2018). This ratio measures the unpredictability of the RR time series and is used to calculate autonomic balance when the follow-up period is not long enough and there is sympathetic activation. SD1/SD2 is correlated with the LF/HF ratio (Shaffer and Ginsberg 2017).

5.2.4 | Results and Effects of Post-Exercise CWI in HRV Recovery

Of the 12 reviewed studies, seven (Bastos et al. 2012; Almeida et al. 2016; Al Haddad, Parouty, and Buchheit 2012; Ravier et al. 2022; Choo et al. 2018; De Oliveira Ottone et al. 2014; Roberts et al. 2015) found statistical significance with $p \leq 0.05$. Eleven studies (Bastos et al. 2012; Stanley, Buchheit, and Peake 2012; Stanley, Peake, and Buchheit 2013b; Stanley et al. 2014; Parouty et al. 2010; Al Haddad, Parouty, and Buchheit 2012; Douglas et al. 2016; Ravier et al. 2022; Choo et al. 2018; De Oliveira Ottone et al. 2014; Roberts et al. 2015) qualitatively assessed the effect size. Some authors (Bastos et al. 2012; Al Haddad et al. 2016; Choo et al. 2018) consider this measure when no significant effects are observed but a trend towards significance is identified ($p < 0.1$). The effect size was calculated according to Cohen's recommendations (Cohen 1988), with confidence intervals ranging from 90% to 95%. Several studies suggest that effect size is better assessed qualitatively through magnitude-based inferences (Hopkins et al. 2009), as effect size can be more relevant for athletic performance than statistical significance (Stanley, Buchheit, and Peake 2012; Stanley, Peake, and Buchheit 2013b; De Oliveira Ottone et al. 2014). Five studies also qualitatively assessed the probability of unknown true differences being smaller than, similar to, or larger than the smallest standard deviation worth mentioning (Stanley, Buchheit, and Peake 2012; Stanley, Peake, and Buchheit 2013b; Stanley et al. 2014; Parouty et al. 2010; Douglas et al. 2016).

Comparing the results, CWI improves cardiac autonomic regulation after exercise compared with active and passive recovery (Bastos et al. 2012). rMSSD values were almost certainly higher after CWI interventions (Stanley, Buchheit, and Peake 2012). CWI was associated with a smaller reduction in rMSSD after swimming sprints (Parouty et al. 2010). The CWI group had higher values compared with the control group (Almeida et al. 2016). rMSSD was higher under CWI conditions compared with immersion in thermoneutral water or the control group (Al Haddad, Parouty, and Buchheit 2012). CWI facilitated cardiac parasympathetic activation after a simulated game (Douglas et al. 2016). Cardiac vagal tone can improve with CWI compared to passive recovery (Ravier et al. 2022).

CWI is effective in increasing parasympathetic reactivation after exercise (Choo et al. 2018) and accelerates this reactivation, although the recovery is short-lived (De Oliveira Ottone et al. 2014). Some studies report short-term parasympathetic reactivation (30 min), but no effects were observed after 4 h (De

Oliveira Ottone et al. 2014). Regarding sports o training, in Stanley, Peake, and Buchheit 2013a, although some parasympathetic indicators improved in relation to aerobic performance, it is suggested that it has a negative impact on high-intensity exercises (Stanley, Peake, and Buchheit 2013b). In sports, greater parasympathetic reactivation was observed in simulated rugby matches, whereas no clear changes were found in repeated sprints (Douglas et al. 2016).

Immediately after CWI, ln rMSSD was higher compared to passive recovery (Stanley, Peake, and Buchheit 2013b). ln rMSSD was likely higher after CWI compared to passive recovery (Stanley et al. 2014), but it was unclear whether the increase occurred during sleep or upon waking (Stanley, Buchheit, and Peake 2012). ln rMSSD rapidly returned to pre-exercise values during water immersion (Roberts et al. 2015). Favorable effects were also found in other HRV indices with CWI post-exercise (Table 1), although no findings were observed in some variables (such as SDNN or LF/HR ratio) (Roberts et al. 2015).

5.2.5 | Proposal for CWI Doses and Other Result Measures

Based on the studies with the best results, the dose we recommend for CWI should comply with some minimum characteristics: CWI should last 5–15 min, at a temperature oscillating between 9°C and 15°C, and at an immersion level from the anterosuperior iliac spine to the neck level. However, the times between sessions should be carefully considered to avoid affecting training (Moore et al. 2022; Peiffer et al. 2010), and especially observing individual response and the preferences of the athlete, and also considering other recovery strategies (Barnett 2006).

Finally, as a result of all of these articles, in relation to a clinical relevance, CWI is an effective strategy to accelerate the parasympathetic activation manifested by your HRV variables, having positive effects on the physical performance of athletes from the point of view of cardiovascular recovery, reducing the risk of accumulative fatigue or injuries for their competitions and training. After this review, a CWI between 5 and 15 min, at temperatures ranging from 9°C to 15°C, is sufficient to promote vagal reactivation but its effects are personalized and begin to appear according to your protocol or intervention, being specific to each athlete or sport.

5.3 | Limitations

One of the main limitations of this study is the inability to conduct a meta-analysis due to differences in the experimental protocols of the reviewed studies. Another significant limitation is the risk of bias in the included studies, detailed in the Results section and in Figure 3. Therefore, it is inadvisable to adopt a categorical conclusion about the effect of CWI on recovery measured by post-exercise HRV. Nevertheless, this is the first systematic review on the recovery response measured by HRV with post-exercise CWI. Further research and higher-quality studies are needed for greater clarity on this topic.

6 | Implications on Physiotherapy Practice

Due to hydrostatic pressure in CWI, a movement of liquid towards the vasculature of the thorax is induced, causing an increase in the central blood volume, systolic volume, cardiac output, and central venous pressure (Wilcock, Cronin, and Hing 2006). This increase in blood volume is believed to stimulate the arterial baroreflex, which in turn, increases parasympathetic activity. Since the heat lost through the skin is more in water than, for example, in air, the peripheral cooling of the body can occur rapidly, especially at rest. Then, CWI could simultaneously trigger baroreceptors (that inhibit sympathetic activity) and cold receptors (that trigger sympathetic activation). In addition, the effects of both CWI and peripheral cooling are accumulative in the strengthening of the parasympathetic control of the heart (Mourot et al. 2008). Both peripheral pressure and central blood volume can last at least 1 h after CWI (Vaile et al. 2011).

7 | Conclusions

This study was designed to research the effect of cold-water immersion on post-exercise recovery measured via HRV in athletes. The results of this study indicate that post-exercise CWI could generate an acute positive effect on parasympathetic reactivation measured via HRV.

Ethics Statement

The authors have nothing to report.

Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study INPLASY 202460117.

Permission to Reproduce Material From Other Sources

The authors have nothing to report.

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