


REVIEW ARTICLE

Influence of physical post-exercise recovery techniques on vagally-mediated heart rate variability: A systematic review and meta-analysis

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Abstract

In sports, physical recovery following exercise-induced fatigue is mediated via the reactivation of the parasympathetic nervous system (PNS). A noninvasive way to quantify the reactivation of the PNS is to assess vagally-mediated heart rate variability (vmHRV), which can then be used as an index of physical recovery. This systematic review and meta-analysis investigated the effects of physical recovery techniques following exercise-induced fatigue on vmHRV, specifically via the root mean square of successive differences (RMSSD). Randomized controlled trials from the databases *PubMed*, *WebOfScience*, and *SportDiscus* were included. Twenty-four studies were part of the systematic review and 17 were included in the meta-analysis. Using physical post-exercise recovery techniques displayed a small to moderate positive effect on RMSSD ($k = 22$, Hedges' $g = 0.40$, 95% confidence interval [CI] = 0.20–0.61, $p = 0.04$) with moderate heterogeneity. In the subgroup analyses, cold water immersion displayed a moderate to large positive effect ($g = 0.75$, 95% CI: 0.42–1.07) compared with none for other techniques. For exercise type, physical recovery techniques performed after resistance exercise ($g = 0.69$, 95% CI: 0.48–0.89) demonstrated a larger positive effect than after cardiovascular intermittent ($g = 0.52$, 95% CI: 0.06–0.97), while physical recovery techniques performed after cardiovascular continuous exercise had no effect. No significant subgroup differences for training status and exercise intensity were observed. Overall, physical post-exercise recovery techniques can accelerate PNS reactivation as indexed by vmHRV, but the effectiveness varies with the technique and exercise type.

KEYWORDS

autonomic nervous system, cardiac vagal activity, cardiac vagal tone, parasympathetic nervous system, physical activity, sport, vagus nerve

Sylvain Laborde and Jannik Wanders shared their first co-authorship.

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1 | INTRODUCTION

The growing physical and psychological demands on athletes, regardless of their expertise level, have created a need for advancing research in sports science, not only to improve training efficiency, but also to enhance the recovery process between training sessions or competitions. Exercise poses metabolic, inflammatory, and thermo-regulatory challenges to various physiological systems in the human body, and recovery describes the ability of these systems to return to homeostasis after exercise cessation (Hausswirth & Le Meur, 2011; Kellmann & Beckmann, 2017; Kellmann et al., 2018). Insufficient recuperation between sessions can lead to athletes' inability to meet the required demands of the subsequent training sessions, higher predisposition to injury and suboptimal performance (Barnett, 2006). Thus, this article focuses on techniques that enhance recovery, and more specifically target the reactivation of the parasympathetic branch of the autonomic nervous system (ANS).

The parasympathetic nervous system (PNS) is essential in recovery because it is closely connected to many psychophysiological processes of self-regulation and self-modulation (Laborde et al., 2018b; Mosley & Laborde, 2022; Smith et al., 2017; Stanley et al., 2013b; Thayer et al., 2009). During exercise, the sympathetic branch of the ANS (PNS counterpart) is predominantly activated (Michael et al., 2017; Seiler et al., 2007; Stanley et al., 2013b). However, an immediate return to higher levels of parasympathetic activation during post-exercise recovery is desired, because it is associated with cardioprotection (de Oliveira Ottone et al., 2014; Ihsan et al., 2016; Jouven et al., 2005), readiness to perform (Ihsan et al., 2016), higher training status (Ihsan et al., 2016) and training responsiveness (de Oliveira Ottone et al., 2014; Ihsan et al., 2016; Schaal et al., 2013). Subsequently, cardiac PNS activity has been proposed as a global marker of athlete recovery (Hautala et al., 2009).

Cardiac PNS activity can be indirectly measured through heart rate variability (HRV) (Berntson et al., 1997; Laborde et al., 2017; Malik et al., 1996). HRV represents the change in time interval between successive heart beats (Berntson et al., 1997; Laborde et al., 2017; Malik et al., 1996). Many HRV parameters can be calculated, and those of interest in the context of recovery are the parameters suggested to reflect cardiac vagal activity, the input of the PNS on cardiac regulation (Berntson et al., 1997; Laborde et al., 2017; Malik et al., 1996). These HRV parameters are also referred to as vagally-mediated HRV (vmHRV) parameters. The preferred time-domain indicator of vmHRV is the root mean square of successive differences (RMSSD), as it is less affected by respiration than frequency-domain vmHRV parameters, such as high-frequency HRV (Penttilä et al., 2001).

Different strategies have been suggested to improve recovery after physical exercise (Barnett, 2006; Dupuy et al., 2018; Peake, 2019; Pelka et al., 2017; Peterson et al., 2015). Active recovery (AR) consists of submaximal physical activity at very low intensity shortly after strenuous exercise to gradually restore the body's homeostasis (Ahmaidi et al., 1996; Ducla-Soares et al., 2007; Ortiz et al., 2019; Soares et al., 2017). Massage therapy, which

involves the hands-on manipulation of soft tissues, aims to enhance health and well-being. It achieves this by applying pressure to these tissues, which is supplemented by the personal touch and a soothing effect (Moyer et al., 2004; Peake, 2019). Compression garments, such as elasticated tights or tops, can amplify the pressure on muscles and limbs, which in turn boosts cardiac output and venous return (Leicht et al., 2020; Peake, 2019). Stretching involves manipulating muscles, tendons and connective tissue to increase the range of motion and prevent injury (Eda et al., 2020; Thacker et al., 2004). Hyperbaric therapy (HT) is a treatment where the subject is placed in a hyperbaric chamber supplemented with pure oxygen for multiple recovery benefits, such as decreased inflammation, vasoconstriction and angiogenesis (Germain et al., 2003). Whole- or partial-body cryotherapy (WPBC) is described as applying extreme cold to the body using dry cold air in a special cryotherapy chamber for its cooling and vasoconstrictive effects (Banfi et al., 2010; Lombardi et al., 2017). Muscle electrostimulation (ES) through superficial electrodes on the skin is used to increase blood flow and accelerate the natural recovery process (Grunovas et al., 2007). Finally, water immersion (WI) techniques refer to the immersion of the body in water intending to improve recovery or injury rehabilitation and can be separated into different categories depending on the temperature (cold [$<15^{\circ}\text{C}$], thermoneutral [16°C – 35°C] or hot [$>36^{\circ}\text{C}$]) (Peake, 2019). They rely on hydrostatic pressure and temperature effects to elicit physiological changes such as increased stroke volume, blood flow and a shift to more PNS activity (Ihsan et al., 2016; Peake, 2019). During contrast water therapy (CWT), the subject alternates between cold and hot water immersions and subsequently vasoconstriction and vasodilation (Bieuzen et al., 2013). For cold water face immersion (CWFI), the subject immerses only their face in cold water—either with simultaneous breath-holding or while breathing through a snorkel—to induce bradycardia, vasoconstriction and stimulate the cold-face receptors (Al Haddad et al., 2010a).

There is a wide range of physical post-exercise recovery techniques and their modes of action vary. The working mechanisms related to RMSSD include hydrostatic pressure (Bieuzen et al., 2013; Ihsan et al., 2016), cold-induced vasoconstriction (Machado et al., 2016; Stephens et al., 2017), heat stimuli (Gendron et al., 2021), stimulation of cold facial receptors (Al Haddad et al., 2010a), increased cardiac output (Leicht et al., 2020; Piras & Gatta, 2017) and alternating vasoconstriction and vasodilation (Bieuzen et al., 2013; Cochrane, 2004). With such variation in the mode of action of these recovery techniques, different effects on the human body and mind can be expected. While some may have greater effects on muscular or metabolic parameters, such as delayed onset muscle soreness (DOMS) or lactate removal, others may affect the ANS more specifically. Previous reviews have tried to compare the effects of these different techniques (e.g., Dupuy et al. (2018) on the magnitude of DOMS and perceived fatigue), but so far, their influence on PNS reactivation has mostly been neglected. Thus, conducting a systematic review with a meta-analysis will help advance recovery research and aid professionals (coaches, athletes, and medical staff) aiming to accelerate the recovery process with the appropriate technique for

their respective disciplines. Consequently, this systematic review and meta-analysis aim to compare the effects of the most common post-exercise physical recovery techniques on the PNS (indirectly measured through vmHRV, indexed with RMSSD) to passive rest and investigate the influence of moderating variables.

2 | METHODS

The systematic review and meta-analysis were pre-registered at the online database PROSPERO (CRD42020210856). The analytic code and extracted data can be found on the Open Science Framework.¹ Preferred Reporting Items For Systematic Reviews and Meta-Analyses (PRISMA) guidelines were applied and followed throughout the review process (Page et al., 2021).

2.1 | Selection criteria and search strategy

PubMed, *Web-Of-Science* and *Scopus* were searched for studies published from inception until 21 June 2021. RMSSD was chosen as the relevant vmHRV parameter because it can reliably reflect cardiac vagal activity (Berntson et al., 1997; Laborde et al., 2017; Malik et al., 1996). Table 1b shows the full search strategy.

Inclusion criteria were based on the PICOS (participants, intervention, control, outcomes, study design) criteria for systematic reviews and meta-analyses (Tacconelli, 2010) and can be found in Table 1a. According to these criteria, non-randomized controlled trials, studies investigating physical recovery techniques without prior exercise-induced fatigue and studies using combinations of physical recovery strategies were excluded. The techniques had to be part of a pre-specified list of the most commonly used physical recovery techniques in practice, with the potential to acutely activate the PNS according to the scientific literature (Barnett, 2006; Dupuy et al., 2018; Peterson et al., 2015). For studies that met inclusion criteria but did not provide the data necessary for inclusion in the meta-analysis, the authors were contacted to obtain the missing data. Studies were excluded from the meta-analysis and only qualitatively analysed as part of the systematic review when the data was not provided.

2.2 | Risk-of-bias assessment

All eligible studies were assessed at the outcome level for potential bias using the Revised Cochrane risk-of-bias tool for randomized trials (RoB2) (Sterne et al., 2019). This tool classifies trials into three levels of bias risk—low, high and some concerns—and consists of five dimensions for potential bias: (1) randomization process, (2) deviations from intended interventions, (3) missing outcome data, (4)

measurement of the outcome, and (5) selection of the reported results.

2.3 | Data extraction and synthesis

Mean and SD of pre and post RMSSD were extracted. Coded moderators were inspired by the aforementioned meta-analysis about the influence of physical recovery techniques on DOMS and muscular inflammatory markers by Dupuy et al. (2018). They included: (1) physical recovery technique type (AR, massage, cold water immersion [CWI], thermoneutral water immersion [TWI], hot water immersion [HWI], CWFI, CWT, WPBC, compression, stretching, ES, and HT); (2) training status (competitive, recreational or inactive); (3) exercise type (cardiorespiratory continuous, cardiorespiratory intermittent or resistance); (4) exercise intensity (very light, light, moderate, vigorous or maximal; according to the criteria of Garber et al., 2011); and (5) exercise duration (in minutes). In case the data of multiple groups had to be pooled together, this was achieved using the formula advised by the Cochrane handbook for systematic reviews (Higgins & Thomas, 2019).

Regarding information related to the HRV measurements, several factors that might influence the interpretation of PNS activity (Laborde et al., 2017) were extracted. These include the measurement position (e.g., lying down, sitting, and standing), the measurement time point (e.g., how much time after exercise), the measurement duration (and, if applicable, which HRV data segment was analyzed from the total HRV measurement duration), and the breathing frequency during the HRV measurement (spontaneous vs. controlled).

2.4 | Statistical analysis

Statistical analysis was conducted using R (version 4.1.0) [40]. Changes in RMSSD values were converted to standardized mean differences (SMD), calculated as Hedges' *g*, to account for small study sample sizes (a frequent occurrence in this meta-analysis) (Durlak, 2009; Lakens, 2013). If multiple measures of the same parameter were used, an averaged Hedges' *g* was calculated. A positive Hedges' *g* denotes an effect arising from the intervention. By convention, effect sizes of 0.2, 0.5 and 0.8 were respectively considered as small, moderate and large (Cohen, 2013). Outcomes across studies were pooled using a random-effects model (Higgins et al., 2022). Between-study heterogeneity was quantified using τ^2 (variance of true effects, using Hedges' estimator (Hedges & Olkin, 1985), and further assessed using I^2 , which provides the percentage of the observed variance reflecting the variance of the true effects rather than sampling error (Higgins et al., 2003). The prediction interval was also computed to consider the potential effect of physical exercise when it is applied within an individual study setting, as this may be different from the average effect (Borenstein & Higgins, 2013; Cochran, 1950; Higgins et al., 2003). The Hartung and Knapp method was used to adjust confidence intervals (CIs) and test statistics (Hartung & Knapp, 2001a, 2001b; Int'Hout et al., 2016).

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TABLE 1 Participants, intervention, control, outcomes, study design (PICOS) criteria (a) and search strategy (b).

a)	
Population	Human, healthy, all genders and ages
Intervention	Physical recovery interventions following exercise: active recovery (AR), massage, cold water immersion (CWI), hot water immersion (HWI), thermoneutral water immersion (TWI), whole- or partial-body therapy (WPBC), compression, stretching, electrostimulation (ES) or hyperbaric therapy (HT)
Control	Passive control condition
Outcome	Vagally-mediated heart rate variability (i.e., root mean square of the successive differences—RMSSD)
Study design	Randomized within-, between-subjects and mixed designs
b)	
Databases	Pubmed, Web of Science, SportDiscus (from inception to 17 June 2021)
Boolean operators	“AND” and “OR”
Keywords	1) recovery techniques: ("immers*" or "cryo*" or "ice pack" or "cooling" or "massage" or "compression" or "hyperbaric" or "electrostimul*" or "active recovery" or "stretch*") 2) HRV terms: ("heart rate variability" or "HRV" or "parasympathetic" or "RSA" or "vagus" or "vagal" or "RMSSD" or "autonomic nervous system" or "autonomic function") 3) postexercise specification: ("after exercise" or "postexercise" or "after training" or "post-training" or "recovery").
Other	Citation network analysis of forward citations and reference lists from papers selected for the full-text step as well as from previous reviews and meta-analyses

Results were visually displayed with forest and funnel plots using R (version 4.1.0) (R Development Core Team, 2022). Between-study heterogeneity was measured through τ^2 (variance of true effects) and further assessed using the I^2 statistic which measures the percentage of the observed variance reflecting the variance of the true effects rather than sampling error (Higgins et al., 2003). The prediction interval was also computed to consider the potential effect of physical recovery techniques on RMSSD when it is applied within an individual study setting, as this may be different from the average effect. A Q-test was performed to evaluate differences between subgroups (Higgins et al., 2003). Subgroup analyses and meta-regression were performed to explore possible causes of heterogeneity (Borenstein & Higgins, 2013). Outliers were detected using a Cook's distance > 1 (Cook, 2015). Potential small study effect and publication bias was assessed by visually inspecting funnel plots of standardized mean difference against standard error and using Egger's test (Egger et al., 1997). If evidence for asymmetry was found ($p < 0.1$ on the Egger's test), the Duval and Tweedie trim-and-fill method was used to quantify the magnitude of the small study effect (Duval & Tweedie, 2000).

3 | RESULTS

3.1 | Study selection

The search process (Figure 1) revealed 419 potentially relevant publications across the databases *WebOfScience* ($k = 135$),

PubMed ($k = 235$), and *SportDiscus* ($k = 49$). After duplicate removal 291 studies published between 1941 and 2021 remained. All studies were then checked for relevancy according to their title ($k = 101$ remaining) and abstract ($k = 43$ remaining). In the end, 43 articles were part of the full-text investigation and 24 met all inclusion criteria. Finally, 17 of them were included in the meta-analysis and seven were included only in the systematic review due to unreported data. The citation network analysis produced 2228 studies, of which 1394 remained in the selection process after duplicate removal, but none were deemed eligible after checking for the inclusion criteria. Overall, four articles examined AR, three massage, 14 CWI, one HWI, three TWI, one CWFI, two CWT, two compression, and two WPBC. No studies were found for stretching, ES or HT. The characteristics of all included studies can be found in Table 2, and the full references can be found in the supplementary material.

3.2 | Risk-of-bias assessment

The results for the individual study risk-of-bias assessments using the “Revised Cochrane RoB2” tool (Sterne et al., 2019) can be found in Table 3. No trials showed low risk-of-bias, six raised some concerns and 28 displayed high risk. In all cases, this was caused by potential bias in the outcome measurement, specifically using photoplethysmography or interbeat intervals (IBI) instead of electrocardiography (ECG). In one trial, possible deviation from the intended interventions provided additional high risk-of-bias.

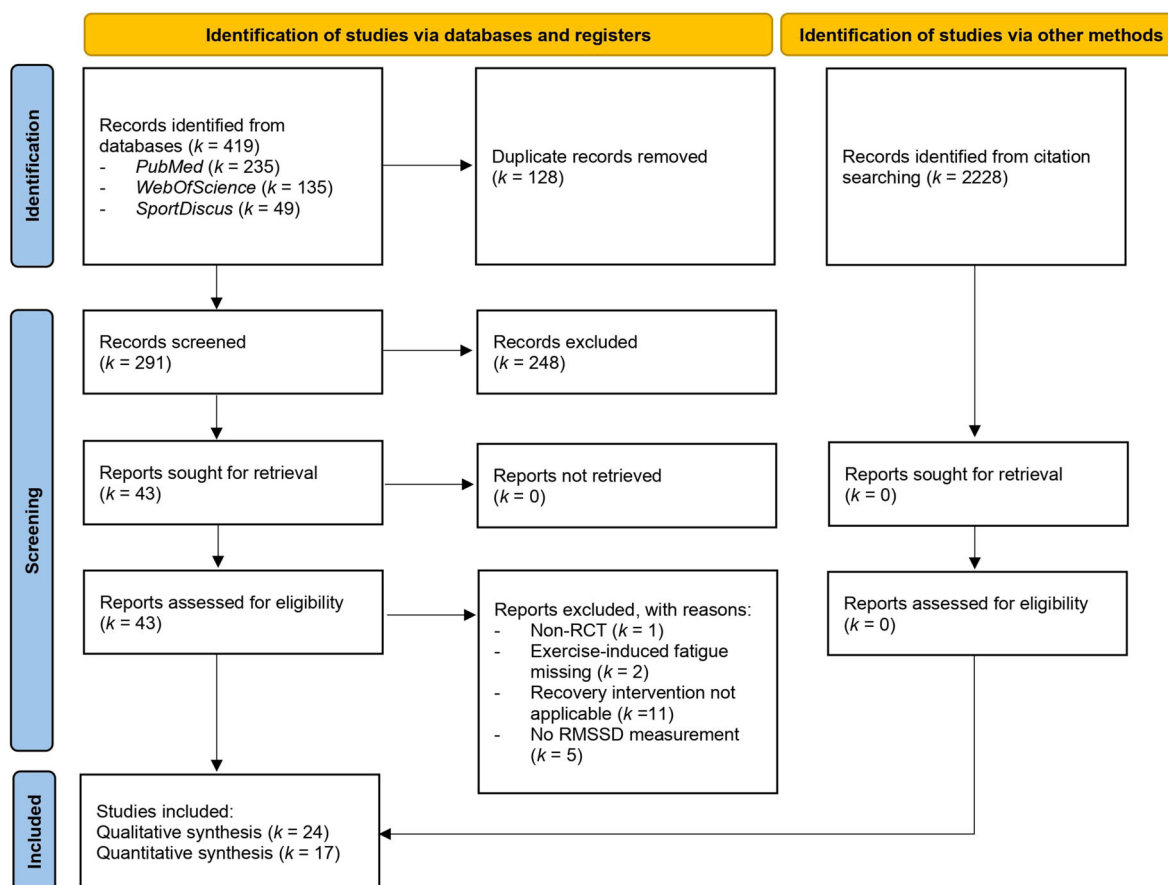


FIGURE 1 PRISMA flow diagram of the selection process of eligible studies.

3.3 | Main analysis

Using physical recovery strategies shortly after exercise compared to passive rest demonstrated a small to moderate positive effect on RMSSD ($k = 22$, $g = 0.40$, 95% CI: 0.20–0.61) compared to passive rest. The heterogeneity was large (prediction interval [−0.24 to 1.05]) with a small to moderate part representing the variance of the true effect ($I^2 = 37.2\%$; $\tau^2 = 0.09$; Figure 2) and the rest being due to sampling error. The prediction interval ($g = -0.24$ to 1.05) also indicated that future studies are four times more likely to have positive effects (null to large) than negative (null to small). Cook's distances (Cook, 2015) were calculated and no outliers were detected. Egger's test for funnel plot asymmetry (Egger et al., 1997) showed a small study effect and potential publication bias ($p = 0.08$) (Figure 3). A trim-and-fill analysis (Duval & Tweedie, 2000) was conducted to correct this and showed no missing studies.

3.4 | Recovery type

CWI ($k = 9$, $g = 0.75$, 95% CI: 0.42–1.07, $I^2 = 11\%$, $\tau^2 = 0.06$), TWI ($k = 3$, $g = 0.17$, 95% CI: −0.53 to 0.87, $I^2 = 0\%$, $\tau^2 = 0$), AR ($k = 2$,

$g = -0.01$, 95% CI: −0.11 to 0.10, $I^2 = 0\%$, $\tau^2 = 0$), massage ($k = 4$, $g = 0.25$, 95% CI: −0.27 to 0.78, $I^2 = 0\%$; $\tau^2 = 0$) and compression ($k = 2$, $g = 0.17$, 95% CI: −2.79 to 3.12, $I^2 = 39\%$; $\tau^2 = 0.06$) showed significantly different effects across the techniques ($Q = 32.85$, $p < 0.01$, $df = 4$; Figure 4). The categories CWFI ($k = 1$, $g = 0.60$, SE:0.28) and HWI ($k = 1$, $g = 0.04$, SE:0.48) each included only one study and thus were excluded from this test. Due to underrepresentation, a post-hoc head-to-head test was only run between CWI and massage. It showed that CWI had a significantly larger effect than massage ($Q = 5.22$, $df = 1$, $p < 0.05$).

3.5 | Exercise type

The effects of resistance ($k = 3$, $g = 0.69$, 95% CI: 0.48–0.89, $I^2 = 0\%$, $\tau^2 = 0.00$), cardiovascular intermittent ($k = 8$, $g = 0.52$, 95% CI: 0.06–0.97, $I^2 = 24\%$, $\tau^2 = 0.19$), and cardiovascular continuous exercise ($k = 11$, $g = 0.29$, 95% CI: −0.01 to 0.59, $I^2 = 44\%$; $\tau^2 = 0.10$) on RMSSD were significantly different from each other [$Q = 7.90$, $p = 0.02$, $df = 2$; Figure 5 [Supporting Information File]]. As resistance exercise was underrepresented, a post-hoc head-to-head test was only run between cardiovascular intermittent

TABLE 2 Characteristics of included studies.

Authors	Population (sex, Age, n)	Exercise characteristics (duration, intensity, type)	HRV measurement point and duration	HRV measurement body position	Breathing frequency during HRV measurement	Recovery characteristics	Control condition	Conclusions
Al Haddad et al. (2010a)	Male; age: 21.6; n = 12	10.5 min; vigorous; card.-continuous (cycling and running)	For 5 min, immediately after the submaximal exercise; last 3 stationary min of the 5-min recovery, average of successive 30 s segments	Sitting (in a water tank for the two water immersion conditions)	Spontaneous	CWI: 5 min at 14.5°C, PR: sitting TWI: 5 min at 33.5°C, submersed to the substernal level in both conditions	PR: sitting	CWI is more effective than TWI at increasing post-exercise PNS reactivation, TWI showed no effect
Al Haddad et al. (2010a)	Male; age: 21.6; n = 13	8 min; vigorous; card.-intermittent (cycling and running)	Immediately after exercise, last 3 stationary min of the 5-min recovery, average of successive 30 s segments	Sitting	Spontaneous (in both conditions with snorkel, wearing a nose clip)	CWFI: 5 min at 11°C	PR: sitting	CWFI can increase post-exercise PNS reactivation
Almeida et al. (2016)	Male; age: 21.73; n = 96	20 min; maximal; card.-intermittent (jumps and cycling)	Recovery starting 1 min after exercise (transition phase); duration: a fixed number of 256 consecutive RR-intervals; during the recovery technique the final 256 RR-intervals; and at 20, 30, 40, 50 and 60 min after exercise (128 RR-intervals before and after each time).	Sitting	Spontaneous	CWI: 5/15 min at 9/14°C, lower body, immersed up to the height of anterior-superior iliac spine, while sitting	PR: sitting	CWI can increase PNS reactivation 50 min after exercise; stimulus CWI 15 min at 14°C found to be the most effective
Araujo et al. (2020)	Male; age: 22.12; n = 11	15.9 min; maximal; card.-continuous (cycling)	Average of successive non-overlapped 30-second segments, from the 5th to the 10th min of the post-exercise recovery period	Sitting	Spontaneous	AR: 5 min of pedalling (60 rpm) at 15W	PR: sitting without pedalling	PNS activity was unaffected by AR
Bastos et al. (2012) ^a	Male; age: 21; n = 20	8.9 min; maximal; card.-continuous (running)	fixed number of 256 consecutive R-R intervals during the last 3 min of each recovery	Standing during the recovery	Spontaneous	AR: 6 min, the subjects walked/ran on the treadmill at a low	PR: standing	Stronger PNS reactivation with CWI in comparison to (Continues)

TABLE 2 (Continued)

Authors	Population (sex, Age, n)	training status	Exercise characteristics (duration, intensity, type)	HRV measurement time point and duration	HRV measurement body position	Breathing frequency during HRV measurement	Recovery characteristics	Control condition	Conclusions
Buchheit et al. (2009)	Male; age: 29; n = 10	Recreational	1.33 min; vigorous; card.-continuous (cycling)	technique intervention; and at 15, 30, 45, 60, 75 and 90 min after exercise	During CWI, participants were submerged in an inflatable water bath whilst sitting After CWI: sitting	Spontaneous	CWI: 5 min at 14°C, submerged to the midsternal level	PR: sitting in an environmental chamber (35.0 ± 0.3°C)	CWI can increase PNS reactivation after vigorous exercise
Chen et al. (2019 – exp 1)	Male; age: 20.04; n = 26	Competitive	2.5 min; vigorous; resistance (running)	15 min, directly after massage	Supine	Not specified	Massage: 30 min	PR: lying down on the massage table	Foot massage may increase PNS after vigorous resistance exercise
Chen et al. (2019 – exp 2)	Male; age: 20.04; n = 26	Competitive	15 min; maximal; card.-intermittent (running)	15 min, directly after massage	Supine	Not specified	Massage: 30 min	PR: lying down on the massage table	No benefit for PNS from foot massage after maximal cardiovascular exercise

TABLE 2 (Continued)

Authors	Population (sex, Age, n)	Exercise characteristics (duration, intensity, type)	training status	HRV measurement time point and duration	HRV measurement body position	Breathing frequency during HRV measurement	Recovery characteristics	Control condition	Conclusions
Choo et al. (2018)	Male; age: 29; n = 9	33.4 min; maximal; card.-continuous (cycling)	Inactive	last 3 min of each 5-min segments recorded at baseline, the end of exercise, during immersion, and 30 min and 60 min post-immersion	Sitting	Spontaneous	CWI: 5 min at 8.6°C or 14.6°C, whole body TWI: 5 min at 35°C, whole body	PR: sitting in an empty bath	CWI can increase PNS reactivation after exercise; TWI showed no effect
de Oliveira Ottone et al. (2014)	Male; age: 24; n = 8	100 min; vigorous; card.-intermittent (eccentric unilateral knee flexion + running)	Recreational	Last 5 min of initial resting, water immersion, post water-immersion, and post-recovery periods	Resting period: supine Experimental conditions: seated in a plastic tank Post-recovery period: supine	Not specified	CWI: 15 min at 15°C, whole body TWI: 15 min at 28°C, whole body HWI: 15 min at 38°C, whole body (immersed to the xiphoid process level, arms out of the water)	PR: sitting in an empty plastic tank	CWI can increase PNS reactivation, while HWI can inhibit it, but these effects are short-lasting. TWI showed no effect
Douglas et al. (2016)	Male; age: 25; n = 10	16 min; vigorous; card. Intermittent (rugby)	Competitive	5 min during CWI/PR and 5 min right after	Sitting, either in a plunge pool for CWI or in ambient condition for PR	Spontaneous	CWI: 5 min at 14°C, whole body (immersed to the neck)	PR: sitting in ambient conditions	CWI can increase PNS reactivation after rugby-related exercise
Flouris et al. (2014a) ^a	Sex unknown; age: 26; n = 9	86.1 min; moderate; card.-continuous, under heat stress (walking)	Recreational	Last 3 min of recovery	Sitting for both PR and CWI; CWI: upright with legs straight in front	Spontaneous	CWI: Ø 6.6 min at 2°C, whole body	PR: upright seated in a 29°C ambient environment	In comparison to PR, CWI does not trigger a faster PNS reactivation after moderate exercise
Flouris et al. (2014b) ^a	Sex unknown; age: 26; n = 9	39.8 min; vigorous; card.-continuous,	Recreational	Last 3 min of recovery	Sitting for both PR and CWI;	Spontaneous	CWI: Ø 11.1 min at 2°C, whole body	PR: upright seated in a 29°C ambient environment	In comparison to PR, CWI does not trigger a faster PNS reactivation

(Continues)

TABLE 2 (Continued)

Authors	Population (sex, Age, n)	training status	Exercise characteristics (duration, intensity, type)	HRV measurement time point and duration	HRV measurement body position	Breathing frequency during HRV measurement	Recovery characteristics	Control condition	Conclusions
Kaesaman (2019)	Male; age: 20.13; n = 16	Recreational	20 min; vigorous; card.-continuous (basket-ball)	During 3 min, immediately after recovery technique (massage vs. PR)	Sitting	Not specified	Massage: 10 min	PR: sitting	Thai massage may increase PNS after basketball exercise
Khan et al. (2020)	Male; age: 19.69; n = 16	Competitive	vigorous; card.-continuous (running)	Last 5 min from the 10 min of ECG recording after the recovery technique	Supine	Controlled (15 cpm)	Compression: 15 min	PR: supine	Compression shows no effect on time-domain indices of HRV
Leicht et al. (2020)	Male; age: 19.8; n = 30	Recreational	10 min; moderate; card.-continuous (cycling)	Final 5 min of 10 min recovery	Supine (with vs. without compression garments)	Spontaneous	Compression: 10 min	PR: supine, without lower body compression garments	PNS activity was unaffected by compression
L'Hermette et al. (2020)	Female; age: 21.4; n = 8	Competitive	81 min; vigorous; card.-intermittent (handball)	Last 5 min of the 10 min following the recovery	CWI: participant pants plunged into water up to their waist Passive recovery: Sitting	Spontaneous	CWI: 14 min at 12°C, lower body	PR: sitting (reclining quietly on a chair)	CWI shows no effect on time-domain indices of HRV
Micheletti et al. (2019)	Male; age: 15.2; n = 41	Recreational	46 min; vigorous; resistance (soccer)	5 min segments, from 0–20 min after training; and then between 40–45 min; 70–75 min; 100–105 min; 115–120 min	Sitting (PR and CWI); for CWI in a plastic pool immersed in 2,400 L of water to the level of	Not specified	CWI: 15 min at 13°C, lower body	PR: sitting	CWI can increase PNS reactivation after soccer training

TABLE 2 (Continued)

Authors	Population (sex, Age, n)	training status	Exercise characteristics (duration, intensity, type)	HRV measurement time point and duration	HRV measurement body position	Breathing frequency during HRV measurement	Recovery characteristics	Control condition	Conclusions
Parouty et al. (2010) ^a	Male; age: 19; n = 10	Competitive	1 min; vigorous; resistance (swimming)	Last 3 min of a 5 min segment measured 15 min after the last sprint	Sitting the anterior superior iliac spine	Spontaneous	CWI: 5 min at 14°C, whole body, participants submerged up to the neck PR: sitting on a chair in ambient room air, 28°C	CWI after exercise increases PNS reactivation, but is detrimental to subsequent swimming performance	
Piras and Gatta (2017) ^a	Male; age: 23.67; n = 9	Competitive	90 min; vigorous; card.-intermittent (weight-lifting)	5 min, from 10' to 15', after 90 min recovery	Supine	Controlled (12–15 cpm)	WPBC: 3 min at -160°C PR: sitting on a chair in the laboratory at 21°C	Tendency towards faster PNS reactivation with PBC, but no significant effect	
Schaal et al. (2013) ^a	Female; age: 20.3; n = 11	Competitive	48 min; maximal; card.-continuous (synchronized swimming ballet)	The last 256 s of 5 min segment, starting 6 min after the end of each of the two exercises	Sitting	Spontaneous	AR: 30 min WPBC: 3 min at -110°C CWT: 15 min at 9/39°C, whole body PR: lying down quietly in a lounge chair placed near the pool for 30 min	WBC increases PNS reactivity largely, CWT showed no effect, AR may inhibit it	
Soares et al. (2017)	Male; age: 20.5; n = 19	Recreational	30 min; vigorous; card.-continuous (cycling)	5 min, 10 to 15 and 25 to 30 min after exercise	Sitting	Spontaneous	AR: 5 min (pedalling at intensity between 30% and 35% heart reserve) PR: sitting on the cycle ergometer during recovery, without pedalling	AR does not influence post-exercise PNS reactivation	
Stanley et al. (2012) ^a	Male; age: 27; n = 18	Competitive	60 min; vigorous; card.-continuous (cycling)	Directly after recovery technique, mean of 5 time points (each 5 min recordings) during the recovery period (Post-45, Post-70, Post-100, Post-130, and Post-190)	Supine	Spontaneous	CWI: 5 min at 14.2°C, whole body CWT: 10 min at 14.2/35.5°C, whole body PR: standing at room temperature (27°C) for 5 min	Both CWI and CWT can increase PNS reactivation after high-intensity cycling, but CWI has a greater effect	

(Continues)

TABLE 2 (Continued)




Authors	Population (sex, Age, n)	Exercise characteristics (duration, intensity, type)	HRV measurement time point and duration	HRV measurement body position	Breathing frequency during HRV measurement	Recovery characteristics	Control condition	Conclusions
Stanley et al. (2013) ^a	Male; age: 27; n = 11	Competitive 120 min; maximal; card-continuous (cycling)	Last 3 min of 5 min segment recordings (post-session and post-recovery)	Sitting	Spontaneous	CWI: 5 min at 10.1°C, standing, whole body	PR: standing at room temperature (27°C)	CWI increases PNS reactivation after exercise, but may reduce physiological adaptation following intense training
Stanley et al. (2014) ^a	Male; age: 25; n = 14	Competitive 12 min; vigorous; resistance (cycling)	Last 3 min of 5 min recording	Sitting (on the ergometer)	Spontaneous	CWI: 5 min at 10°C, lower body (immersed standing up to the level of their umbilicus)	PR: standing at room temperature (27°C)	CWI increases PNS reactivation after high-intensity cycling
Zhong et al. (2018)	Male; age: 19.15; n = 12	Competitive 2.1 min; vigorous; resistance (reverse sit-ups)	5 min, immediately after the recovery, and 24 h later	Sitting	Not specified	Massage: 20 min (supine on a mechanical massage bed)	PR: supine (on the same mechanical massage bed, switched off)	Back massage shows no effect on time-domain HRV indices

Abbreviations: AR, active recovery; CPM, cycles per minute (for breathing frequency); CWI, cold water immersion; CWT, contrast water therapy; CWFI, cold water face immersion; HRV, heart rate variability; n, sample size; PNS reactivation, parasympathetic nervous system reactivation (here inferred via RMSSD, the root mean square of successive differences); PR, passive recovery; TWI, thermoneutral water immersion; WPBC, whole- or partial body cryotherapy.

^aStudies only present in the systematic review.

TABLE 3 Risk-of-bias analysis results.

	Randomisation process	Deviations from interventions	Missing outcome data	Measurement of the outcome	Selection of the reported results	Overall risk-of-bias
Al Haddad et al. (2010a)	!	+	+	-	!	-
Al Haddad et al. (2010b)	!	+	+	-	!	-
Almeida et al. (2016)	+	+	+	-	!	-
Araujo et al. (2020)	!	+	+	-	!	-
Bastos et al. (2012)	!	+	+	-	!	-
Buchheit et al. (2009)	!	+	+	-	!	-
Chen et al. (2019)	!	+	+	+	!	!
Choo et al. (2018)	!	+	+	-	!	-
de Oliveira Ottone et al. (2014)	!	+	+	-	!	-
Douglas et al. (2016)	!	+	+	-	!	-
Flouris et al. (2014a)	!	+	+	+	!	!
Flouris et al. (2014b)	!	+	+	+	!	!
Kaesaman (2019)	!	+	+	-	!	-
Khan et al. (2020)	+	+	+	+	!	!
Leicht et al. (2020)	!	+	+	-	!	-
L'Hermette et al. (2020)	!	+	+	-	!	-
Micheletti et al. (2019)	+	+	+	-	+	-
Parouty et al. (2010)	!	-	+	-	!	-
Piras and Gatta (2017)	!	+	+	-	!	-
Schaal et al. (2013)	!	+	+	-	!	-
Soares et al. (2017)	!	+	+	-	!	-
Stanley et al. (2012)	!	+	+	-	!	-
Stanley et al. (2013a)	!	+	+	-	!	-
Stanley et al. (2014)	!	+	+	-	!	-
Zhong et al. (2018)	!	+	+	+	!	!

 Low risk
 Some concerns
 High risk

and cardiovascular continuous exercise. It showed no significant difference between the two techniques ($Q = 0.92$, $df = 1$, $p = 0.33$) suggesting that the difference in the primary test was due to the reduced heterogeneity in the moderate to large effects reported in the resistance exercise category. While the effect of these two exercise modes could not be differed, only cardiovascular intermittent exercise showed a significant positive effect between neutral and large.

3.6 | Training status

The effects of inactive ($k = 2$, $g = 0.21$, 95% CI: -1.90 to 2.31, $I^2 = 0\%$, $\tau^2 = 0.00$), recreational ($k = 13$, $g = 0.32$, 95% CI: 0.07-0.57, $I^2 = 34\%$, $\tau^2 = 0.10$) and competitive ($k = 7$, $g = 0.64$, 95% CI: 0.13-1.15, $I^2 = 44\%$, $\tau^2 = 0.15$) training status on RMSSD were not significantly different from each other ($Q = 2.77$, $p = 0.25$, $df = 2$; Figure 6 [Supporting Information File]). As the inactive category was largely

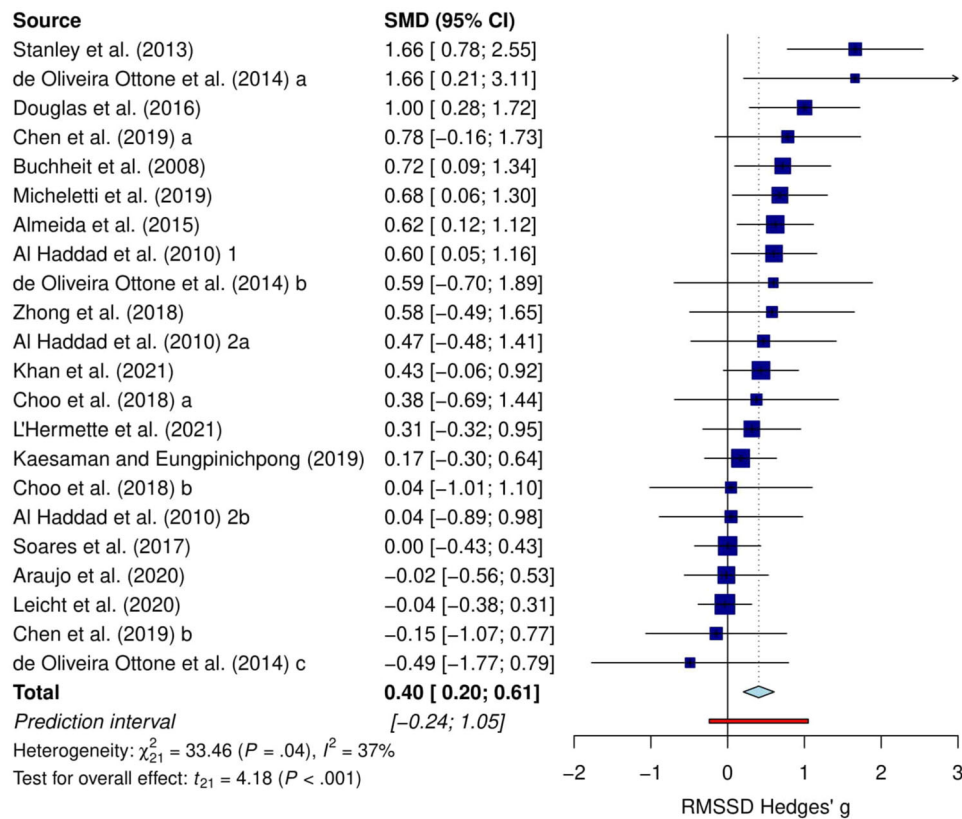


FIGURE 2 Forest plot comparing the influence of physical recovery techniques on RMSSD versus passive rest. Squares represent the individual studies' Hedges' g . Diamond represents overall Hedges' g . Thin lines represent 95% CIs. Thick line represents prediction interval. Square size signifies weight within meta-analysis. CIs, confidence intervals; RMSSD, root mean square of successive differences.

underrepresented, a head-to-head test between recreational and competitive status was performed. It showed no significant difference between the two categories ($Q = 1.83$, $df = 1$, $p = 0.18$), suggesting that training status is not a moderator of RMSSD response.

3.7 | Exercise intensity

Vigorous ($k = 15$, $g = 0.44$, 95% CI: 0.23–0.65, $I^2 = 9\%$, $\tau^2 = 0.03$) and maximal ($k = 6$, $g = 0.42$, 95% CI: −0.26 to 1.11, $I^2 = 60\%$, $\tau^2 = 0.26$) exercise intensity exhibited no significantly different effects on RMSSD ($Q = 0.00$, $p = 0.95$, $df = 1$; Figure 7 [Supporting Information File]). While vigorous exercise intensity showed a significant individual effect, it should be considered that the test for subgroup differences was not significant suggesting that exercise intensity is not a major moderator of RMSSD response. Moderate intensity was excluded from the analysis due to underrepresentation.

3.8 | Exercise duration

A meta regression was conducted for the continuous moderator exercise duration and revealed no significant effect ($k = 21$, $\beta = 0.01$, $r^2 = 12.63\%$, $p = 0.15$).

4 | DISCUSSION

4.1 | Main findings

To the authors' knowledge, this systematic review and meta-analysis was the first to investigate the effect of a single postexercise physical recovery session on PNS reactivation, indexed by RMSSD. The results displayed that using a physical recovery strategy after exercise increases RMSSD when compared to passive rest ($g = 0.40$ 95% CI: 0.20–0.61; small to moderate effect), thus potentially improving recovery processes. The subgroup analyses have shown that the results are influenced by physical recovery techniques. No further differences were detected. However, this needs to be interpreted with caution due to the underrepresentation of some subgroups. Furthermore, the visual inspection of the funnel plot revealed a slight asymmetry, which was confirmed by Egger's test ($p = 0.08$). It suggests a potential small study effect or publication bias.

CWI was the only physical recovery technique with a significant effect on RMSSD post-exercise regarding the different physical recovery types. Indeed, it was supported by all studies in the qualitative analysis, with only de Oliveira Ottone et al. (2014) observing just a positive tendency without statistical significance. These findings are in accordance with the review of Versey et al.

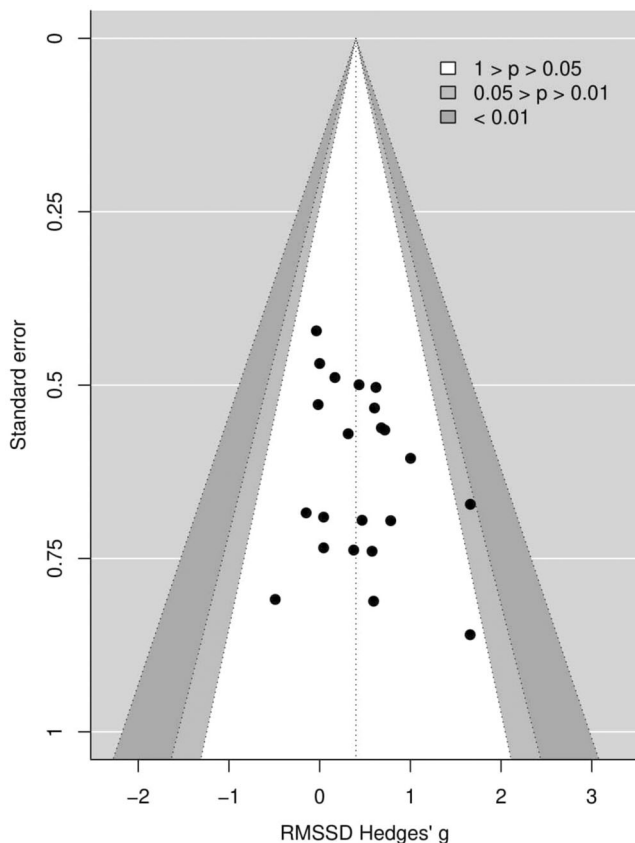


FIGURE 3 Funnel plot for the main analysis. RMSSD, root mean square of successive differences.

(2013), who found an increase of most HRV indices through CWI. Moreover, Ihsan et al. (2016) describe it as a fitting method to enhance PNS reactivation due to its effects on the cardiovascular system, such as augmented central blood volume and subsequently increased stroke volume and cardiac output. Subsequently, these mechanisms lead to higher baroreceptor activation, which triggers a stimulation of the PNS to reduce heart rate. The authors attribute these changes to two primary mechanisms: hydrostatic pressure and cold-induced vasoconstriction. The subgroup analysis found no similar effect for TWI, suggesting that without sufficient vasoconstriction induced by the cold stimulus, baroreceptor stimulation may not be sufficient, and parasympathetic activation is not enhanced. However, due to the clear underrepresentation of both TWI and HWI, no definite conclusions should be made until more research is available. Likewise, no definite conclusions can be made for CWFI as only one study used it (moderate effect). In the study, Al Haddad et al. (2010a) found that it appears to be a simple, effective and inexpensive strategy to accelerate PNS reactivation. Additionally, the potential for increasing PNS activity was shown by previous studies outside of the exercise context (Ackermann et al., 2022; Eckberg et al., 1984; Finley et al., 1979; Hayashi et al., 1997; Kinoshita et al., 2006). Still, more research should be conducted to determine if it can elicit similar effects to CWI on the PNS, even though most of the body is not actually immersed in water. It could

be hypothesized that the impact of the facial cold receptors is strong enough to compensate for the lower hydrostatic pressure induced by this technique.

Both CWT and WPBC could not be included in the meta-analysis, but have shown potential to increase post-exercise RMSSD in the qualitative analysis. In one study for CWT, Stanley et al. (2013a) observed a significant increase of RMSSD—albeit a greater effect for CWI—and for WPBC Schaal et al. (2013) found WBC at -110°C to greatly accelerate it compared to passive rest. Overall, some effect on post-exercise PNS reactivation elicited by a cold stimulus seems likely. However, the different techniques cannot be compared objectively at this point due to a lack of randomized controlled trials.

Similarly, the impact of massage therapy on RMSSD remains unclear ($g = 0.25$, 95% CI: -0.27 to 0.78), requiring additional research. Amongst the included studies, Zhong et al. (2018) and Kaesaman (2019) reported an increase of RMSSD after mechanical-bed massage, and Chen et al. (2019) observed an enhanced PNS reactivation with foot massage after resistance exercise, but none after cardiovascular exercise. These varying effects may be explained by a variation in the used massage techniques (Moyer et al., 2004), which included Thai, foot, and mechanical-bed massage. Overall, while massage therapy seems to potentially influence PNS reactivation, the number of available studies is too low to make definitive conclusions.

AR and compression showed mixed results and were both underrepresented in the meta-analysis, therefore no assumptions can be made for these techniques at this point. Since a lack of studies is apparent for all techniques, it would be unwise to draw firm conclusions from this subgroup analysis. However, it is possible to improve PNS reactivation after exercise using physical recovery techniques instead of passive rest. Furthermore, not all techniques elicit the same effects, which should be considered when choosing a physical recovery strategy as a practitioner.

The subgroup analysis for training status showed no significant difference between the groups. However, a neutral to moderate effect for recreational and a small to large effect for competitive training status were observed. Given the small number of studies in the inactive subset, it is unclear where the effect lies for sedentary populations, but previous literature states that more trained athletes have higher vmHRV compared to a sedentary population (Aubert et al., 2003; Sandercocock et al., 2005) and that PNS recovery is more rapid in athletes with higher aerobic fitness (Seiler et al., 2007; Stanley et al., 2013b). It could be therefore hypothesized that PNS reactivation could be improved in the long-term or even be a relevant training goal. If an athlete could train to improve PNS reactivation, it could in theory facilitate readiness to perform and training responsiveness and ultimately lead to a competitive advantage. This would be especially relevant in competitive phases, which require faster recovery. However, the results of this meta-analysis do not clearly indicate this, as there was no significant result in the test for subgroup differences.

In the exercise parameters, no effect for duration was found in the meta-regression. For exercise intensity, a small to moderate

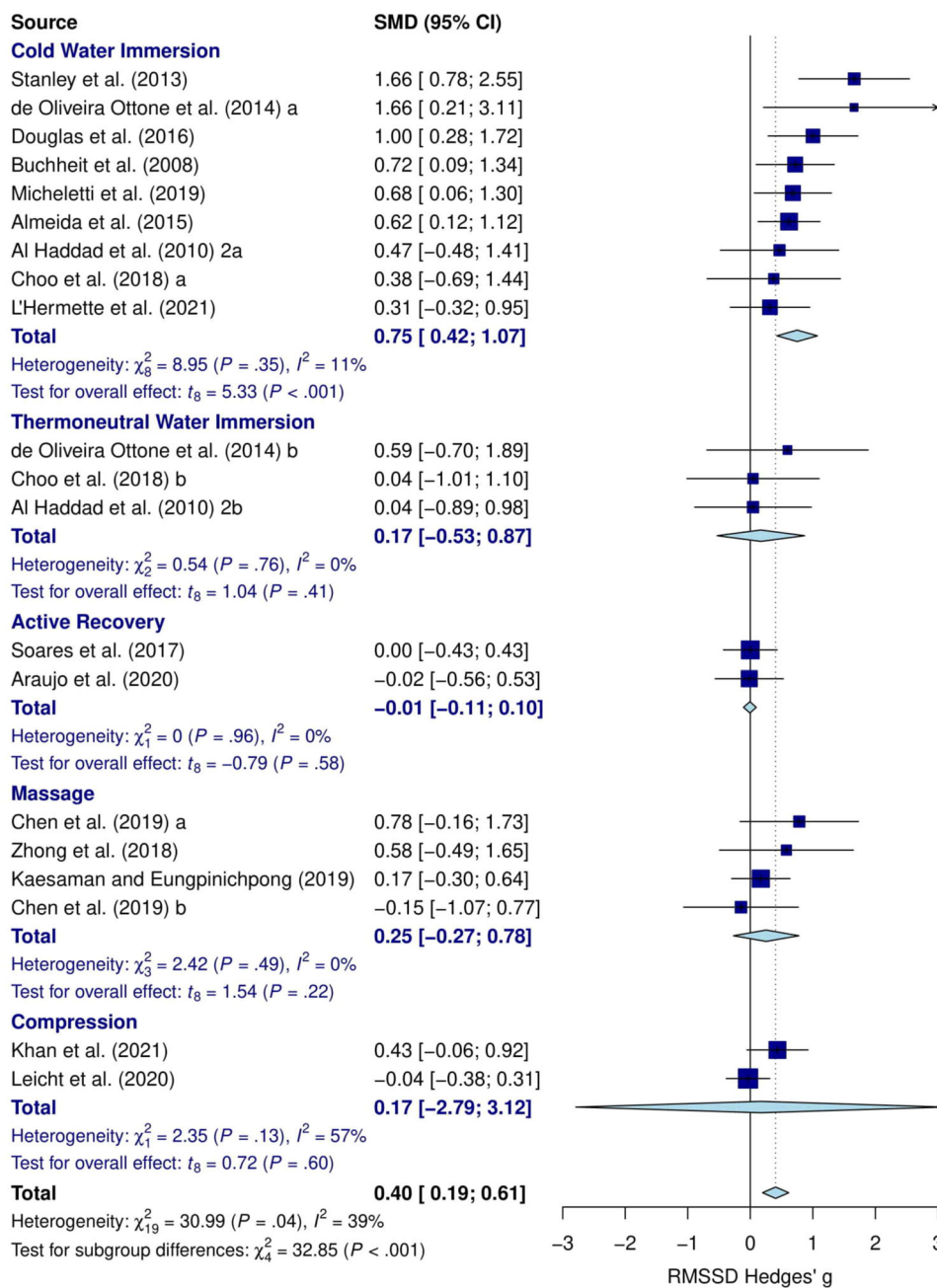


FIGURE 4 Forest plot for the subgroup analysis of physical recovery types. Squares represent the individual studies' Hedges' g . Diamonds represent overall Hedges' g . Lines represent 95% CIs. Square size signifies weight within meta-analysis. CIs, confidence intervals; RMSSD, root mean square of successive differences.

effect for vigorous intensity was observed, although the test for subgroup differences showed no significant differences between the groups. Previous studies discovered that it takes longer for PNS activity to recover to pre-exercise levels after higher-intensity training (Seiler et al., 2007; Stanley et al., 2013b), but in contrast to that assumption, no effect for maximal intensity was found. Since additionally moderate intensity was severely underrepresented, no strong conclusions about the effects of exercise intensity on post-exercise RMSSD should be drawn at this point. Regarding the type of exercise, a significant difference between the groups was observed.

Specifically, resistance exercise demonstrated a moderate to large effect and cardiovascular intermittent exercise exhibited a neutral to moderate effect. Taking these findings, we might postulate that different sports have different effects on the PNS. For example, it could be hypothesized that sports with continuous cardiovascular exercise like swimming, cycling, or running at low or moderate intensities have less impact on the PNS than sports with high-intensity intermittent sprints or resistance exercise, such as basketball, handball, or weightlifting. Therefore, it may be useful for practitioners to consider these variables. The research shows that

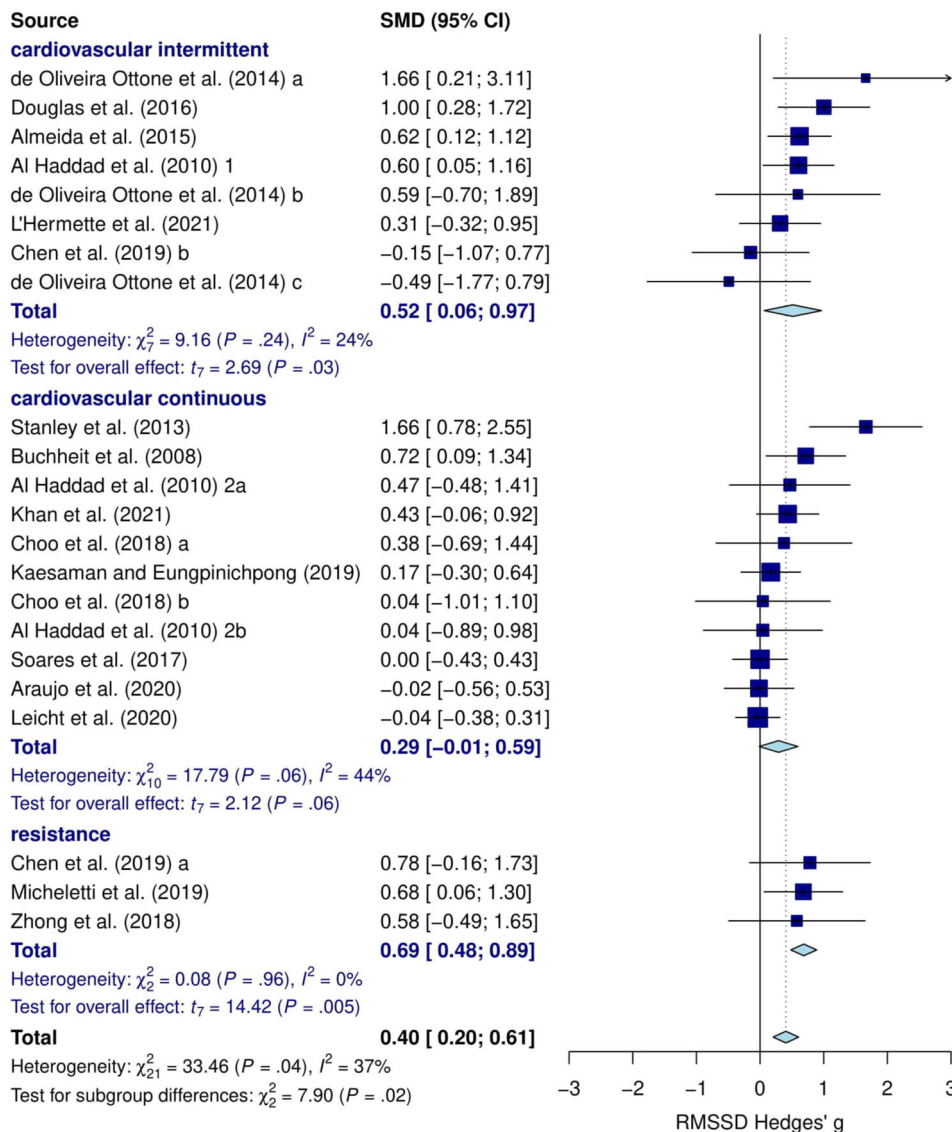


FIGURE 5 Forest plot for the subgroup analysis of exercise type. CIs, confidence intervals; RMSSD, root mean square of successive differences.

effects of resistance and cardiovascular intermittent exercises are similar and cardiovascular continuous exercise also shows a tendency to increase RMSSD, subsequently more research into this moderator is necessary.

4.2 | Practical implications

While using physical recovery techniques after exercise to increase PNS activity can be recommended based on this review, athletes, coaches, medical personnel, and other practitioners should carefully consider which technique to use since not all show beneficial effects. Only CWI can be recommended. CWFI, CWT and WPBC may be beneficial to achieve PNS reactivation, but not enough research has been conducted to draw sound conclusions at present.

Recovery consists of multiple aspects outside of PNS activity (e.g., muscular recovery, perceived fatigue, subsequent performance, and injury prevention), therefore, practitioners need to think carefully about what their goal of post-exercise recovery is. Techniques like AR and HWI show some promise for lactate removal and muscular recovery (Barnett, 2006; Dupuy et al., 2018; Peake, 2019), but this review indicates this may come at the cost of potentially worse PNS reactivation compared to other techniques. A better combined recovery may be provided by CWI, WPBC and massage therapy, as these techniques show benefits in muscular and metabolic aspects of recovery according to previous research (Barnett, 2006; Dupuy et al., 2018; Peake, 2019; Peterson et al., 2015) and potentially positive effects on the PNS. CWFI could be an easy to administer technique specializing in PNS reactivation, but since it is only focused on a small part of the body, no effect on muscular recovery is to be expected. Using a combination of different recovery techniques (e.g.,

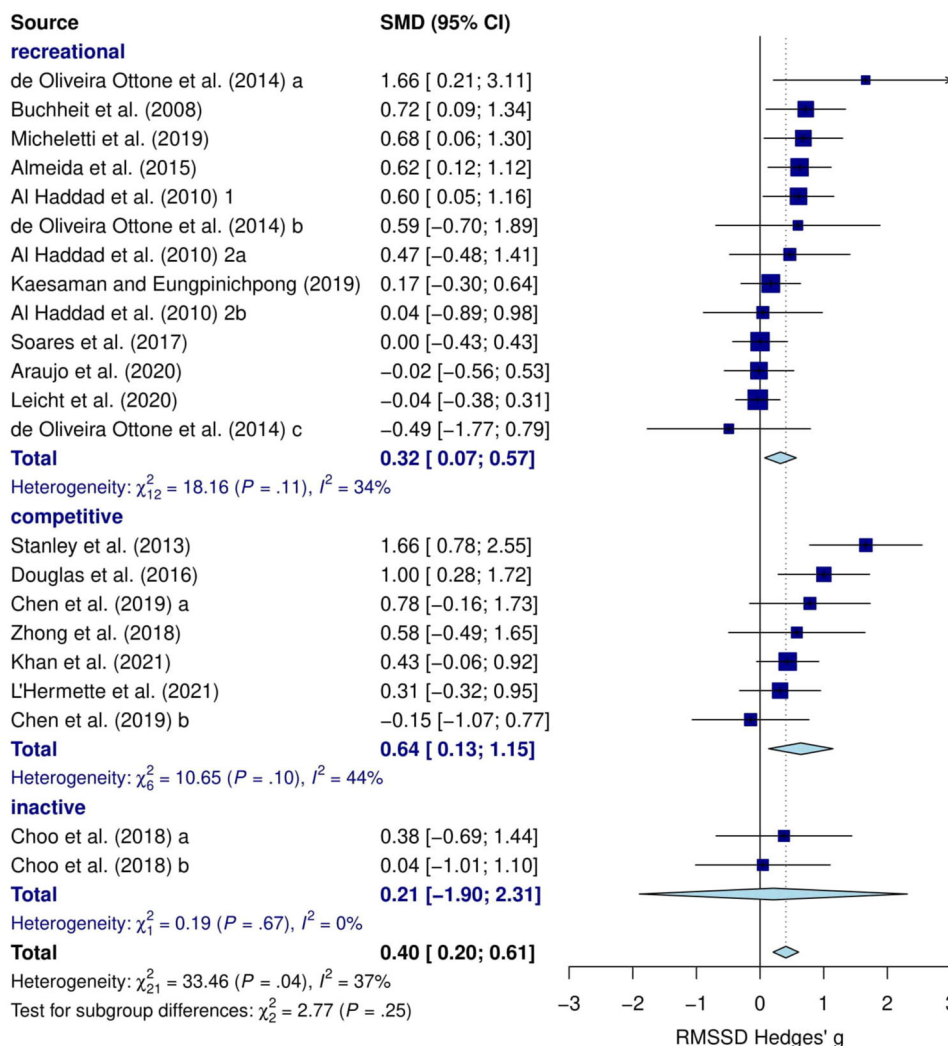


FIGURE 6 Forest plot for the subgroup analysis of training status. CIs, confidence intervals; RMSSD, root mean square of successive differences.

CWFI with a subsequent massage session) may bring more clarity to this issue. Still, research into the effect of various combinations on the ANS is missing currently. Combining techniques should be examined in the future to provide better insight into how the different aspects of recovery interact and how to improve them without impairing one another.

Finally, another important consideration is that some physical recovery techniques are much more feasible in a real-life setting than others. For example, AR can be done after practice or competition at any level, while WPBC needs specialized equipment and monitoring that is likely only available in professional sports. This means that the effects of physical recovery interventions need to outweigh their logistical constraints. While this is highly dependent on the sport, in this meta-analysis evidence for it was only found for CWI. An argument could be made for CWFI since it is easy to administer, quick, and inexpensive (Al Haddad et al., 2010a), but more research is required to understand its impact on the PNS (Ackermann et al., 2022), and its limited effects on muscular parameters need to be considered.

In a professional sports environment, massage therapy is very common after exercise, and the infrastructure for it already exists, therefore thorough investigations into its effects on the PNS are also recommended.

4.3 | Limitations

While this review provides interesting insight into the capabilities of post-exercise physical recovery techniques for increasing PNS activity, some limitations must be considered. First, no speculation can be made about stretching, ES or HT, as no studies using these techniques met our inclusion criteria. Additionally, physical recovery techniques not mentioned in previous reviews and meta-analyses (Barnett, 2006; Dupuy et al., 2018; Peterson et al., 2015) and whose use has recently developed, such as foam rolling and whole-body vibration, may require further investigation regarding their influence on PNS activity in the future. Second, beyond the physical recovery

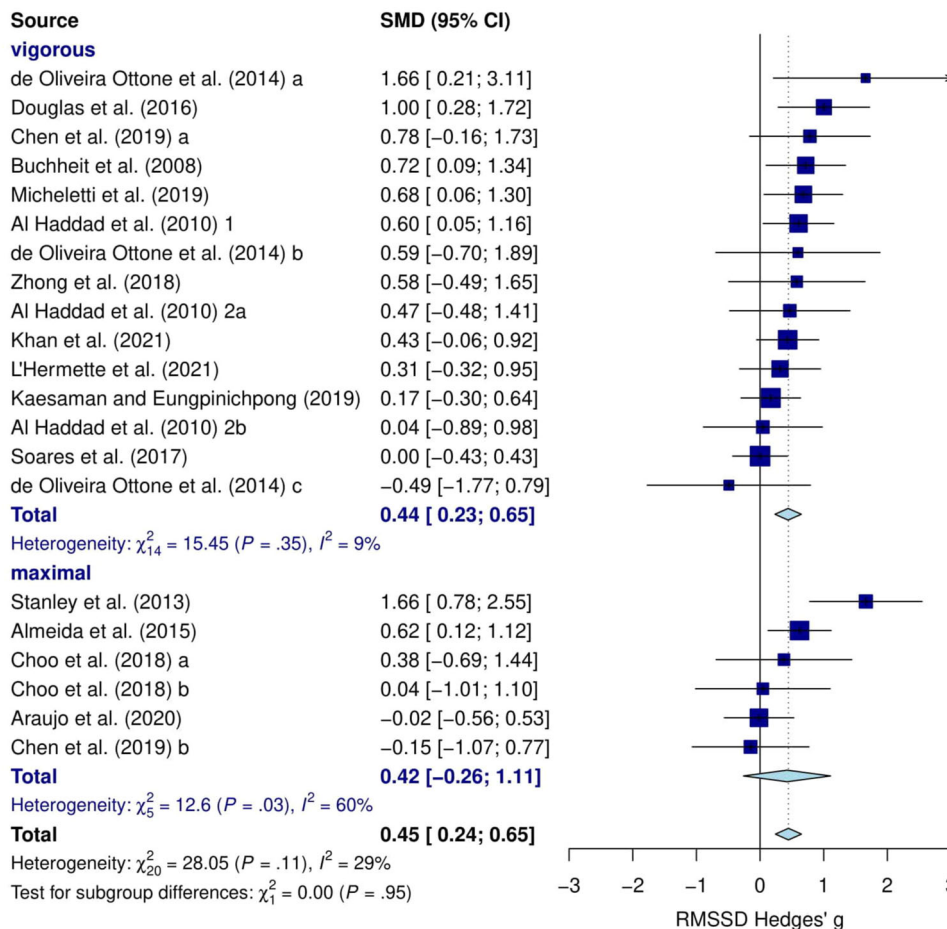


FIGURE 7 Forest plot for the subgroup analysis of exercise intensity. CIs, confidence intervals; RMSSD, root mean square of successive differences.

techniques taken into account in this systematic review and meta-analysis, some additional techniques known to enhance vmHRV, such as non-invasive brain stimulation (Schmaußer et al., 2022), slow-paced breathing (Laborde et al., 2022; Laborde et al., 2022; Mosley et al., 2023; Perez-Gaido et al., 2021; Sevoz-Couche & Laborde, 2022), as well as psychological relaxation techniques (e.g., Pelka et al., 2017) still have to be tested within the context of post-exercise recovery together with vmHRV measurements. Third, some moderators were underrepresented, limiting our conclusions. Fourth, risk-of-bias needs to be considered since overall bias concerns were found in all studies. Fifth, most studies' primary source of bias was measuring HRV with photoplethysmography or IBIs (using heart rate monitors), instead of ECG. The prevalence of these measurement methods is cause for concern since they are known to be less reliable (Laborde et al., 2017; Quintana et al., 2016). ECG usage for HRV measurements should be a focus of researchers in the future, even though it may come at a higher cost. Sixth, the fluctuating nature of HRV measurements regarding movement and posture must be considered, as some observed techniques differ significantly in their procedure: involving a lot of movement (AR), completed in a supine (massage), sitting (CWI and CWFI) or standing (WPBC) position. Similarly, additionally to posture and movement, a range of factors

potentially impacting HRV measurements have to be considered and standardized (Fatisson et al., 2016; Laborde et al., 2018a). Seventh, breathing rate should be spontaneous and not controlled, to allow the natural return to physiological baseline levels after exercise, and given it may otherwise alter the interpretation of PNS reactivation based on vmHRV measurement (Laborde et al., 2017; Larsen et al., 2010; Stanley et al., 2013b). Eighth, the average sample size in the studies included was rather small (mean $N = 18.2$, $SD = 17.8$). Ninth, an amendment was made to the initial PROSPERO protocol. To enable to connect the current meta-analysis to existing HRV research and theories related to recovery (Bellenger et al., 2016; Laborde et al., 2018b; Mosley & Laborde, 2022; Smith et al., 2017; Stanley et al., 2013b; Thayer et al., 2009), it was decided to restrict the focus to vmHRV, and to choose a single main outcome variable, RMSSD.

Nevertheless, it should be noted that this meta-analysis is the first to review and compare the influence of several physical recovery interventions on PNS reactivation, indexed by RMSSD. It can give important insight for interested parties (coaches, athletes, sports scientists etc.) into the role of the PNS in recovery, which has so far been neglected in favour of other markers, such as DOMS, lactate removal or perceived fatigue.

5 | CONCLUSION

In conclusion, this systematic review and meta-analysis showed that post-exercise physical recovery techniques can potentially accelerate PNS recovery by increasing RMSSD. This effect varies with the different strategies, with CWI showing the most robust results. The exercise type can also impact PNS recovery after exercise. Overall, this work can be seen as a first examination into the effects of different recovery modalities on the PNS, but not enough studies about each modality exist to make definitive conclusions. Therefore, more research on all individual techniques is needed to clarify these results. Furthermore, it should be examined whether using multiple recovery techniques in combination provides more benefits for the PNS and better global recovery.

AUTHOR CONTRIBUTIONS

The search, risk-of-bias assessments, criteria assessments, and data extraction were conducted by Jannik Wanders with the help of Sylvain Laborde. Interpretation of results was done by Jannik Wanders, Sylvain Laborde, and Florian Javelle. The manuscript was drafted by Jannik Wanders and edited by Sylvain Laborde, Florian Javelle, and Emma Mosley. The framework for the statistical analysis was developed by Florian Javelle. Language editing was done by Emma Mosley.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data generated or analysed during this study are accessible via the Open Science Framework: 10.17605/OSF.IO/BVSC4

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