Received: 21 September 2022 | Accepted: 14 September 2023

DOI: 10.1111/cpf.12855

Clinical Physiology and Functional Imaging

REVIEW ARTICLE

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

Sylvain Laborde[1,2] | Jannik Wanders[1] | Emma Mosley[3] | Florian Javelle[4]

[1]Department of Performance Psychology, Institute of Psychology, German Sport University Cologne, Cologne, Germany

[2]UFR STAPS, Normandie Université, Caen, France

[3]Solent University Southampton, Southampton, UK

[4]NeuroPsychoImmunology Research Unit, Department of Molecular and Cellular Sports Medicine, Institute for Cardiovascular Research and Sports Medicine, German Sport University Cologne, Cologne, Germany

Correspondence
Sylvain Laborde, German Sport University Cologne, Am Sportpark Müngersdorf 6, 50933 Cologne, Germany.
Email: s.laborde@dshs-koeln.de

Funding information
Projekt DEAL

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.

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 thermoregulatory challenges to various physiological systems in the human body, and recovery describes the ability of these systems to return to homoeostasis 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 homoeostasis (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°C], thermoneutral [16°C–35°C] or hot [>36°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 Hedge's 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; IntHout et al., 2016).

[1]10.17605/OSF.IO/BVSC4.

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.

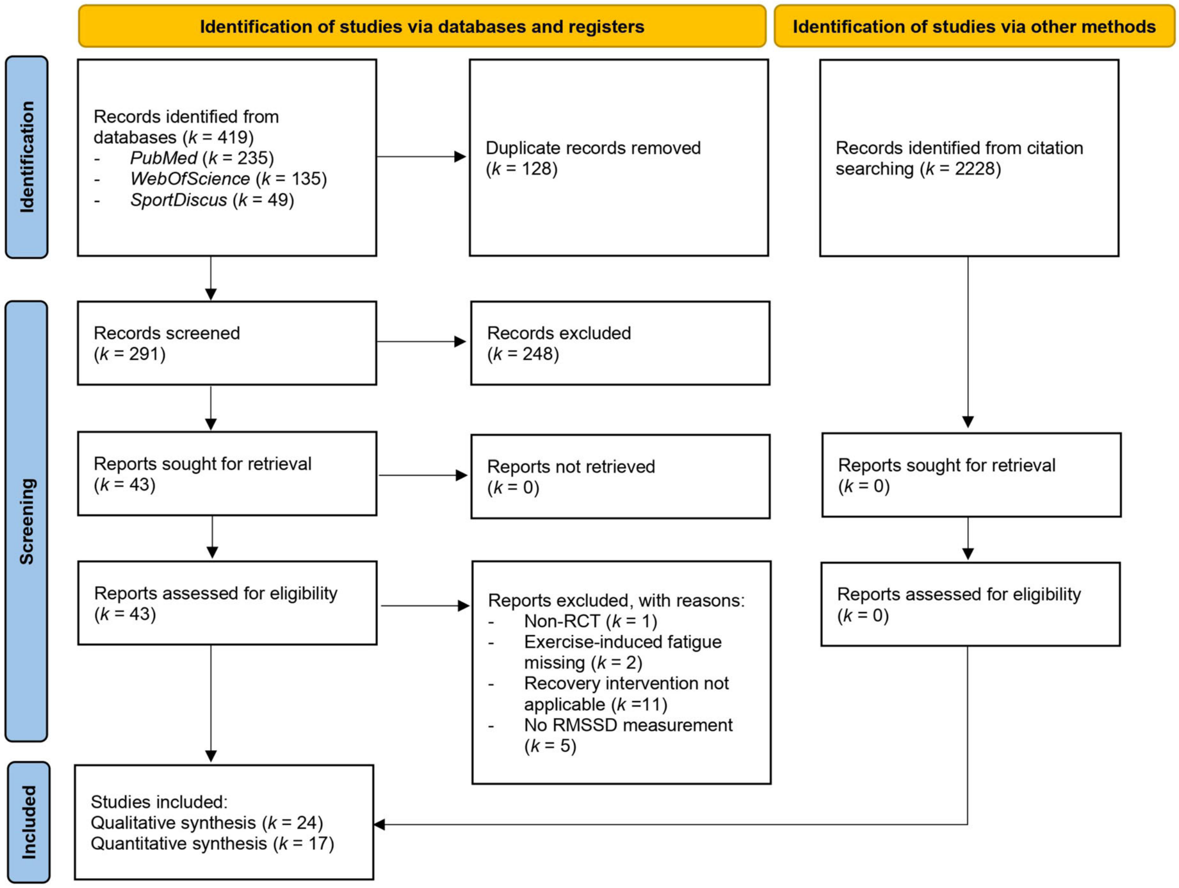

FIGURE 1 PRISMA flow diagram of the selection process of eligible studies.

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*)	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
Al Haddad et al. (2010a)	Male; age: 21.6; *n* = 12	Recreational	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, 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	Recreational	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	Recreational	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	Recreational	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 15 W	PR: sitting without pedalling	PNS activity was unaffected by AR
Bastos et al. (2012)[a]	Male; age: 21; *n* = 20	Recreational	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

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
				technique intervention; and at 15, 30, 45, 60, 75 and 90 min after exercise	technique (6 min) Supine after the recovery technique		intensity (30% of VO2max) CWI: 6 min at 11°C: participants submerged standing at a level that covered the anterior superior iliac spine		PR 30 min after exercise cessation
Buchheit et al. (2009)	Male; age: 29; *n* = 10	Recreational	1.33 min; vigorous; card.-continuous (cycling)	CWI occurred from 7.5 to 12.5 min of the 20-min recovery period after supramaximal exercise 1; then supramaximal exercise 2 took place directly after recovery period 1 HRV analysis was performed with 30 s intervals RMSSD averaged over 3 min, between 3 min and 6 min of recovery after supramaximal exercise 2	During CWI, partici-pants 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

(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
Choo et al. (2018)	Male; age: 29; n = 9	Inactive	33.4 min; maximal; card.-continuous (cycling)	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	Recreational	100 min; vigorous; card.-intermittent (eccentric unilateral knee flexion + running)	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	Competitive	16 min; vigorous; card. Intermittent (rugby)	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	Recreational	86.1 min; moderate; card.-continuous, under heat stress (walking)	Last 3 min of recovery	Sitting for both PR and CWI; CWI: upright with legs straight in front	Spontaneous	CWI: ∅ 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	Recreational	39.8 min; vigorous; card.-continuous,	Last 3 min of recovery	Sitting for both PR and CWI; CWI:	Spontaneous	CWI: ∅ 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

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
			under heat stress (running)		upright with legs straight in front				after vigorous exercise
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 compres-sion 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: partici-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

(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
					the anterior superior iliac spine				
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	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

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
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.

[a]Studies 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

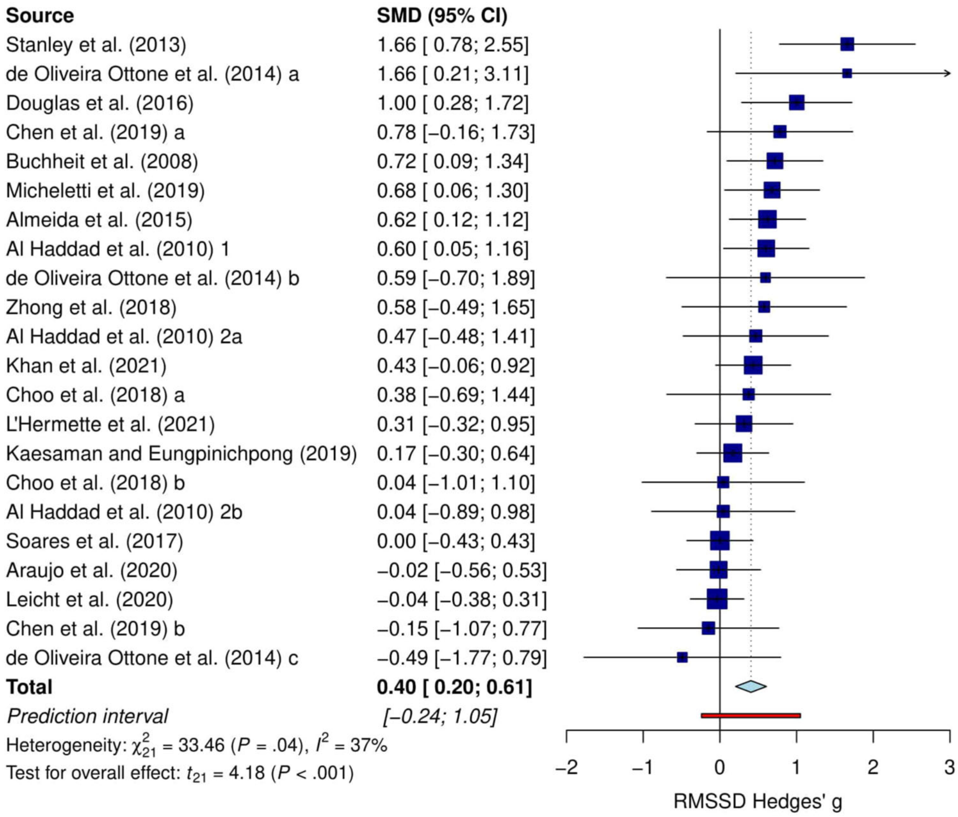

FIGURE 2 Forest plot comparing the influence of physical recovery techniques on RMSSD versus passive rest. Squares represent the individual studies' Hedges' *g*. Diamond represents overall Hedges' *g*. Thin lines represent 95% CIs. Thick line represents prediction interval. Square size signifies weight 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.

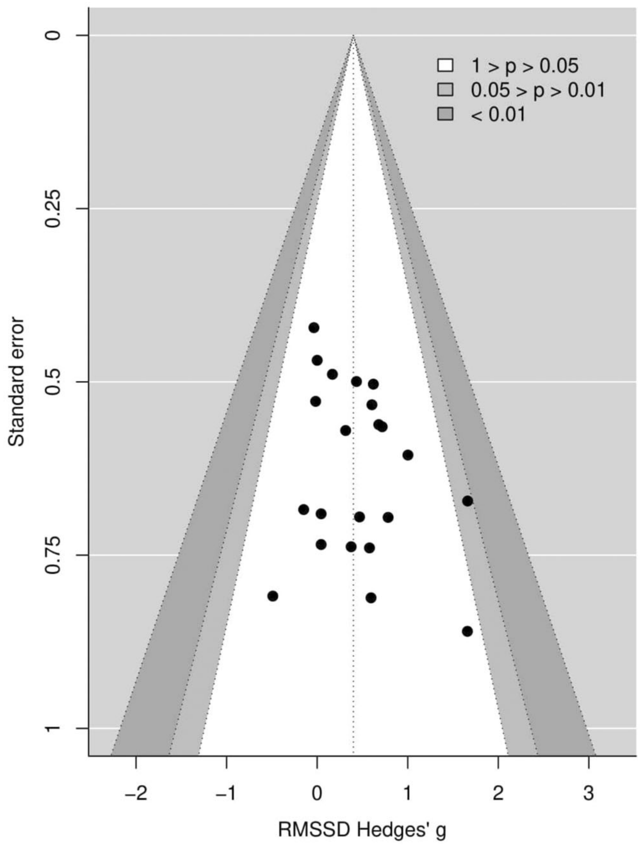

FIGURE 3 Funnel plot for the main analysis. RMSSD, root mean square of successive differences.

(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; Sandercock 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

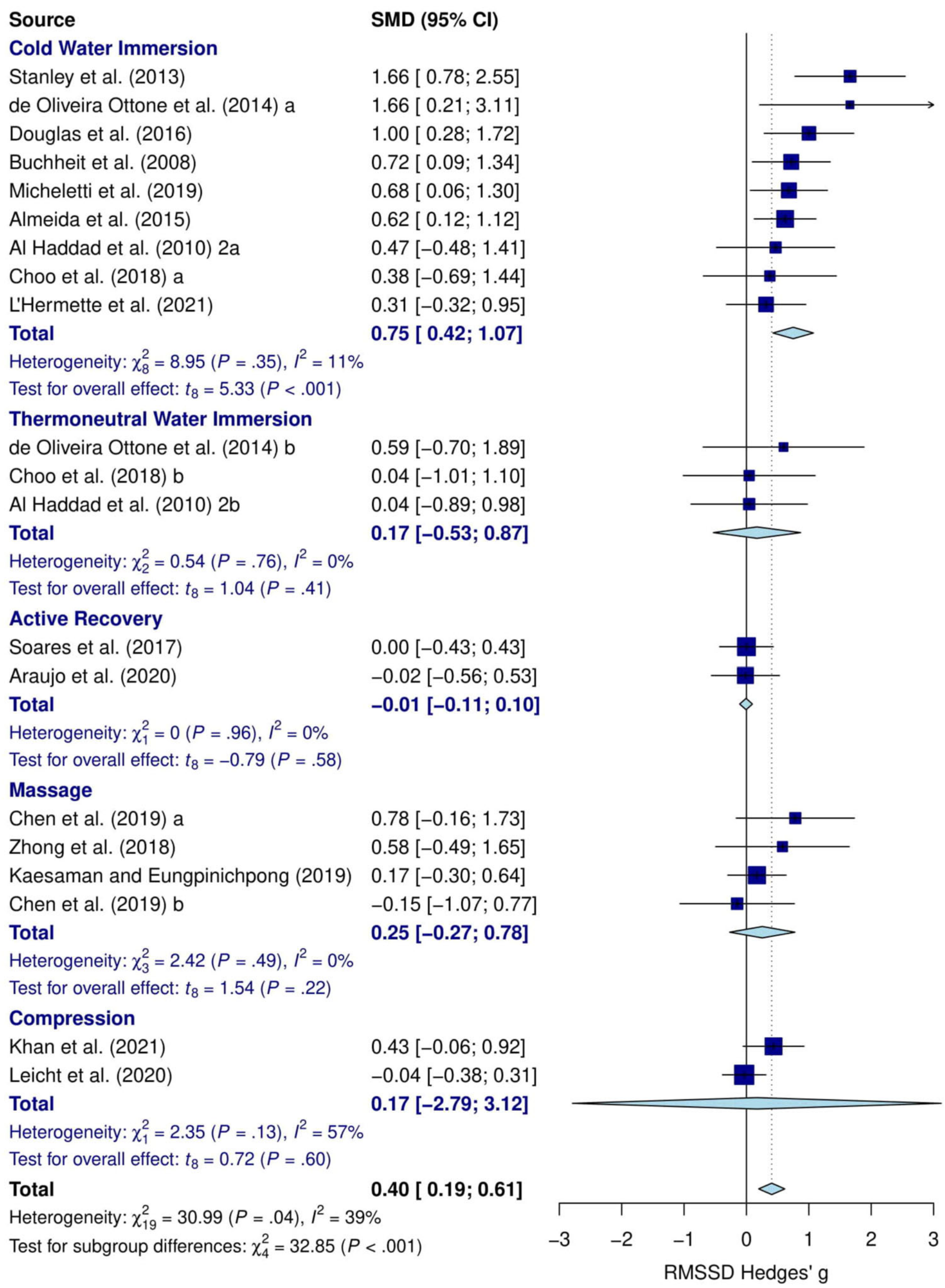

FIGURE 4 Forest plot for the subgroup analysis of physical recovery types. Squares represent the individual studies' Hedges' *g*. Diamonds represent overall Hedges' *g*. Lines represent 95% CIs. Square size signifies weight within meta-analysis. CIs, confidence intervals; RMSSD, root mean square of successive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

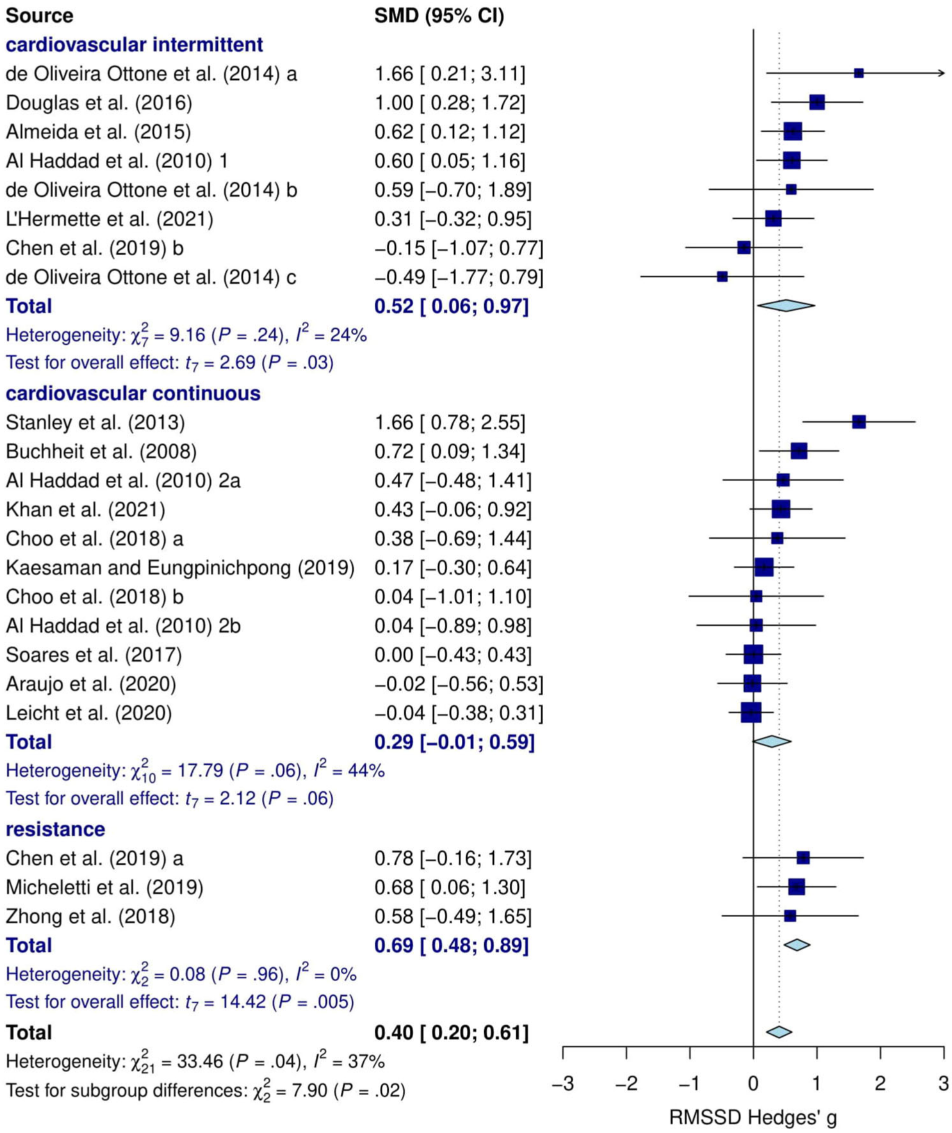

FIGURE 5 Forest plot for the subgroup analysis of exercise type. CIs, confidence intervals; RMSSD, root mean square of successive differences.

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.,

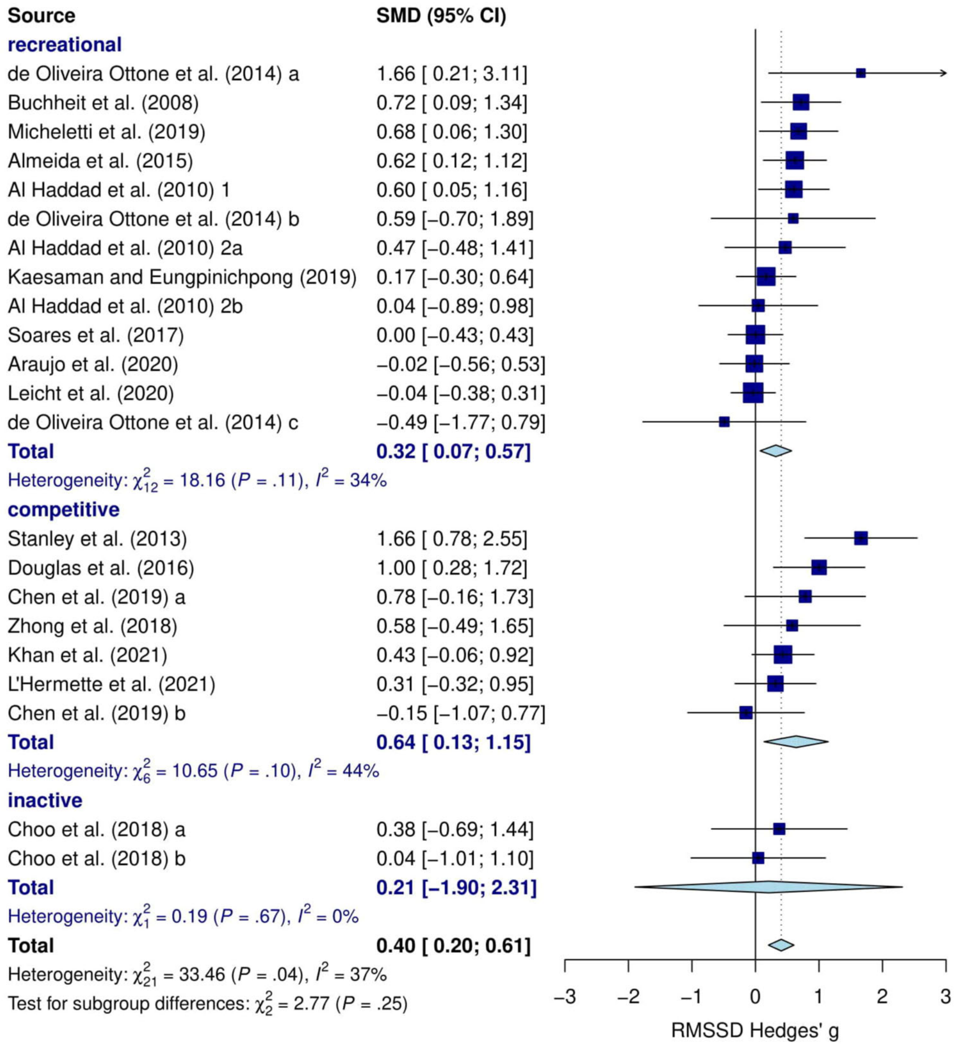

FIGURE 6 Forest plot for the subgroup analysis of training status. CIs, confidence intervals; RMSSD, root mean square of successive differences.

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

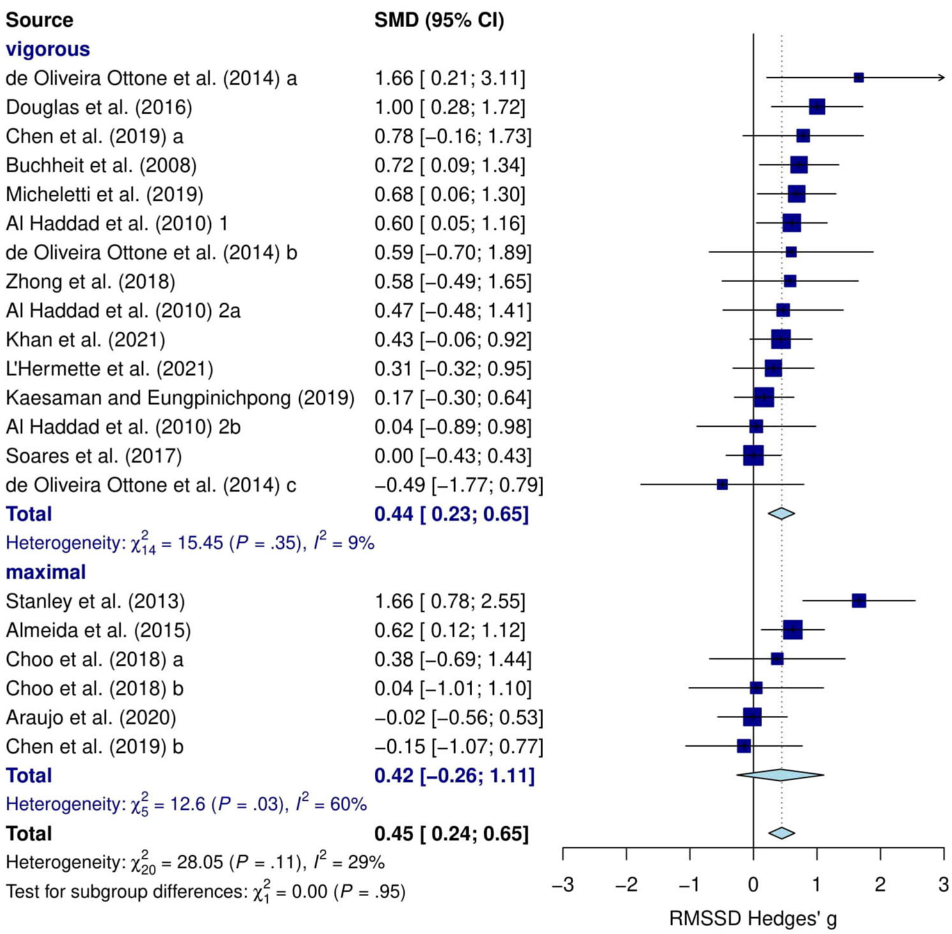

FIGURE 7 Forest plot for the subgroup analysis of exercise intensity. CIs, confidence intervals; RMSSD, root mean square of successive differences.

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). Nineth, 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.

ACKNOWLEDGMENTS

We have no specific acknowledgements to mention in the article. Open Access funding enabled and organized by Projekt DEAL.

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

ORCID

Sylvain Laborde https://orcid.org/0000-0003-4842-6548

REFERENCES

Ackermann, S.P., Raab, M., Backschat, S., Smith, D.J.C., Javelle, F. & Laborde, S. (2022) The diving response and cardiac vagal activity: a systematic review and meta-analysis. *Psychophysiology*, 60, e14183. Available from: https://doi.org/10.1111/psyp.14183

Ahmaidi, S., Granier, P., Taoutaou, Z., Mercier, J., Dubouchaud, H. & Prefaut, C. (1996) Effects of active recovery on plasma lactate and anaerobic power following repeated intensive exercise. *Medicine and Science in Sports and Exercise*, 28(4), 450–456. Available from: https://doi.org/10.1097/00005768-199604000-00009

Al Haddad, H., Laursen, P.B., Ahmaidi, S. & Buchheit, M. (2010a) Influence of cold water face immersion on post-exercise parasympathetic reactivation. *European Journal of Applied Physiology*, 108(3), 599–606. Available from: https://doi.org/10.1007/s00421-009-1253-9

Al Haddad, H., Laursen, P.B., Chollet, D., Lemaitre, F., Ahmaidi, S. & Buchheit, M. (2010b) Effect of cold or thermoneutral water immersion on post-exercise heart rate recovery and heart rate variability indices. *Auton Neurosci*, 156(1–2), 111–116. https://doi.org/10.1016/j.autneu.2010.03.017

Almeida, A.C., Machado, A.F., Albuquerque, M.C., Netto, L.M., Vanderlei, F.M., Vanderlei, L.C. et al. (2016) The effects of cold water immersion with different dosages (duration and temperature variations) on heart rate variability post-exercise recovery: a randomized controlled trial. *Journal of Science and Medicine in Sport*, 19(8), 676–681. https://doi.org/10.1016/j.jsams.2015.10.003

Araujo, J.A., Pecanha, T., Novelli, F.I., Mello, C.S.A., Moreira-Goncalves, D., Arsa, G. et al. (2020) Reproducibility of heart rate variability Indices at post-maximal exercise. *International Journal of Sports Medicine*, 41(8), 512–519. https://doi.org/10.1055/a-1114-6297

Aubert, E., Seps, B. & Beckers, F. (2003) Heart rate variability in athletes. *Sports Medicine*, 33(12), 889–919. Available from: https://doi.org/10.2165/00007256-200333120-00003

Banfi, G., Lombardi, G., Colombini, A. & Melegati, G. (2010) Whole-body cryotherapy in athletes. *Sports Medicine*, 40(6), 509–517. Available from: https://doi.org/10.2165/11531940-000000000-00000

Barnett, A. (2006) Using recovery modalities between training sessions in elite athletes: does it help? *Sports Medicine*, 36(9), 781–796. Available from: https://doi.org/10.2165/00007256-200636090-00005

Bastos, F.N., Vanderlei, L.C., Nakamura, F.Y., Bertollo, M., Godoy, M.F., Hoshi, R.A. et al. (2012) Effects of cold water immersion and active recovery on post-exercise heart rate variability. *International Journal of Sports Medicine*, 33(11), 873–879. https://doi.org/10.1055/s-0032-1301905

Bellenger, C.R., Fuller, J.T., Thomson, R.L., Davison, K., Robertson, E.Y. & Buckley, J.D. (2016) Monitoring athletic training status through autonomic heart rate regulation: a systematic review and meta-analysis. *Sports Medicine*, 46(10), 1461–1486. Available from: https://doi.org/10.1007/s40279-016-0484-2

Berntson, G.G., Thomas Bigger, J., Eckberg, D.L., Grossman, P., Kaufmann, P.G., Malik, M. et al. (1997) Heart rate variability: origins, methods, and interpretive caveats. *Psychophysiology*, 34, 623–648. Available from: https://doi.org/10.1111/j.1469-8986.1997.tb02140.x

Bieuzen, F., Bleakley, C.M. & Costello, J.T. (2013) Contrast water therapy and exercise induced muscle damage: a systematic review and meta-analysis. *PLoS One*, 8(4), e62356. Available from: https://doi.org/10.1371/journal.pone.0062356

Borenstein, M. & Higgins, J.P.T. (2013) Meta-analysis and subgroups. *Prevention Science*, 14(2), 134–143. Available from: https://doi.org/10.1007/s11121-013-0377-7

Buchheit, M., Millet, G.P., Parisy, A., Pourchez, S., Laursen, P.B. & Ahmaidi, S. (2008) Supramaximal training and postexercise parasympathetic reactivation in adolescents. *Medicine & Science in Sports & Exercise*, 40(2), 362–371. https://doi.org/10.1249/mss.0b013e31815aa2ee

Buchheit, M., Peiffer, J.J., Abbiss, C.R. & Laursen, P.B. (2009) Effect of cold water immersion on postexercise parasympathetic reactivation. *American Journal of Physiology - Heart and Circulatory Physiology*, 296(2), H421–H427. https://doi.org/10.1152/ajpheart.01017.2008

Chen, Y.S., Lu, W.A., Clemente, F.M., Bezerra, J.P. & Kuo, C.D. (2019) Increased parasympathetic activity by foot reflexology massage after repeated sprint test in collegiate football players: a randomised controlled trial. *Sports*, 7(11), 228. Available from: https://doi.org/10.3390/sports7110228

Choo, H.C., Nosaka, K., Peiffer, J.J., Ihsan, M., Yeo, C.C. & Abbiss, C.R. (2018) Effect of water immersion temperature on heart rate variability following exercise in the heat. *Kinesiology*, 50(1), 67–74 https://hrcak.srce.hr/ojs/index.php/kinesiology/article/view/6342

Cochran, W.G. (1950) The comparison of percentages in matched samples. *Biometrika*, 37(3–4), 256–266. Available from: https://doi.org/10.1093/biomet/37.3-4.256

Cochrane, D.J. (2004) Alternating hot and cold water immersion for athlete recovery: a review. *Physical Therapy in Sport*, 5(1), 26–32. Available from: https://doi.org/10.1016/j.ptsp.2003.10.002

Cohen, J. (2013) *Statistical power analysis for the behavioral sciences*. Burlington: Elsevier Science.

Cook, R.D. (2015) Detection of influential observation in linear regression. *Technometrics*, 19(1), 15–18. Available from: https://doi.org/10.1080/00401706.1977.10489493

Douglas, J., Plews, D.J., Handcock, P.J. & Rehrer, N.J. (2016) The Beneficial Effect of Parasympathetic Reactivation on Sympathetic Drive During Simulated Rugby Sevens. *Int J Sports Physiol Perform*, 11(4), 480–488. https://doi.org/10.1123/ijspp.2015-0317

Ducla-Soares, J.L., Santos-Bento, M., Laranjo, S., Andrade, a, Ducla-Soares, E., Boto, J.P. et al. (2007) Wavelet analysis of autonomic outflow of normal subjects on head-up tilt, cold pressor test, valsalva manoeuvre and deep breathing. *Experimental Physiology*, 92, 677–686. Available from: https://doi.org/10.1113/expphysiol.2007.038026

Dupuy, O., Douzi, W., Theurot, D., Bosquet, L. & Dugué, B. (2018) An evidence-based approach for choosing post-exercise recovery techniques to reduce markers of muscle damage, soreness, fatigue, and inflammation: a systematic review with meta-analysis. *Frontiers in Physiology*, 9, 403. Available from: https://doi.org/10.3389/fphys.2018.00403

Durlak, J.A. (2009) How to select, calculate, and interpret effect sizes. *Journal of Pediatric Psychology*, 34(9), 917–928. Available from: https://doi.org/10.1093/jpepsy/jsp004

Duval, S. & Tweedie, R. (2000) Trim and fill: A simple funnel-plot-based method of testing and adjusting for publication bias in meta-analysis. *Biometrics*, 56(2), 455–463.

Eckberg, D.L., Mohanty, S.K. & Raczkowska, M. (1984) Trigeminal-baroreceptor reflex interactions modulate human cardiac vagal efferent activity. *The Journal of Physiology*, 347, 75–83. Available from: https://doi.org/10.1113/jphysiol.1984.sp015054

Eda, N., Ito, H. & Akama, T. (2020) Beneficial effects of yoga stretching on salivary stress hormones and parasympathetic nerve activity. *Journal of Sports Science & Medicine*, 19(4), 695–702.

Egger, M., Smith, G.D., Schneider, M. & Minder, C. (1997) Bias in meta-analysis detected by a simple, graphical test. *BMJ*, 315(7109), 629–634. Available from: https://doi.org/10.1136/bmj.315.7109.629

Fatisson, J., Oswald, V. & Lalonde, F. (2016) Influence diagram of physiological and environmental factors affecting heart rate variability: an extended literature overview. *Heart International*, 11(1), heartint.500023. Available from: https://doi.org/10.5301/heartint.5000232

Finley, J.P., Bonet, J.F. & Waxman, M.B. (1979) Autonomic pathways responsible for bradycardia on facial immersion. *Journal of Applied Physiology*, 47(6), 1218–1222. Available from: https://doi.org/10.1152/jappl.1979.47.6.1218

Flouris, A.D., Bravi, A., Wright-Beatty, H.E., Green, G., Seely, A.J. & Kenny, G.P. (2014a) Heart rate variability during exertional heat stress: effects of heat production and treatment. *European Journal of Applied Physiology*, 114(4), 785–792. https://doi.org/10.1007/s00421-013-2804-7

Flouris, A.D., Poirier, M.P., Bravi, A., Wright-Beatty, H.E., Herry, C., Seely, A.J. et al. (2014b) Changes in heart rate variability during the induction and decay of heat acclimation. *European Journal of Applied Physiology*, 114(10), 2119–2128. https://doi.org/10.1007/s00421-014-2935-5

Garber, C.E., Blissmer, B., Deschenes, M.R., Franklin, B.A., Lamonte, M.J., Lee, I.M. et al. (2011) American college of sports Medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise. *Medicine and Science in Sports and Exercise*, 43(7), 1334–1359. Available from: https://doi.org/10.1249/MSS.0b013e318213fefb

Gendron, P., Gravel, H., Barry, H. & Gagnon, D. (2021) Seven days of hot water heat acclimation does not modulate the change in heart rate variability during passive heat exposure. *Applied Physiology, Nutrition, and Metabolism*, 46(3), 257–264. Available from: https://doi.org/10.1139/apnm-2020-0510

Germain, G., Delaney, J., Moore, G., Lee, P., Lacroix, V. & Montgomery, D. (2003) Effect of hyperbaric oxygen therapy on exercise-induced muscle soreness. *Undersea & Hyperbaric Medicine*, 30(2), 135–145.

Grunovas, A., Silinskas, V., Poderys, J. & Trinkunas, E. (2007) Peripheral and systemic circulation after local dynamic exercise and recovery using passive foot movement and electrostimulation. *The Journal of Sports Medicine and Physical Fitness*, 47(3), 335–343.

Hartung, J. & Knapp, G. (2001a) On tests of the overall treatment effect in meta-analysis with normally distributed responses. *Statistics in Medicine*, 20(12), 1771–1782. Available from: https://doi.org/10.1002/sim.791

Hartung, J. & Knapp, G. (2001b) A refined method for the meta-analysis of controlled clinical trials with binary outcome. *Statistics in Medicine*, 20(24), 3875–3889. Available from: https://doi.org/10.1002/sim.1009

Hausswirth, C. & Le Meur, Y. (2011) Physiological and nutritional aspects of post-exercise recovery: specific recommendations for female athletes. *Sports Medicine*, 41(10), 861–882. Available from: https://doi.org/10.2165/11593180-000000000-00000

Hautala, A.J., Kiviniemi, A.M. & Tulppo, M.P. (2009) Individual responses to aerobic exercise: the role of the autonomic nervous system. *Neuroscience & Biobehavioral Reviews*, 33, 107–115. Available from: https://doi.org/10.1016/j.neubiorev.2008.04.009

Hayashi, N., Ishihara, M., Tanaka, A., Osumi, T. & Yoshida, T. (1997) Face immersion increases vagal activity as assessed by heart rate variability. *European Journal of Applied Physiology*, 76(5), 394–399. Available from: https://doi.org/10.1007/s004210050267

Hedges, L.V. & Olkin, I. (1985) *Statistical methods for meta-analysis*. San Diego, CA: Academic Press.

Higgins, J.P. & Thomas, J. (2019) *Cochrane handbook for systematic reviews of interventions*. Chichester (UK): John Wiley & Sons.

Higgins, J.P., Thomas, J., Chandler, J., Cumpston, M., Li, T. & Page, M.J. et al. (2022) *Cochrane handbook for systematic reviews of interventions*, 6.3 ed. Hoboken, New Jersey: Wiley-Blackwell.

Higgins, J.P.T. (2003) Measuring inconsistency in meta-analyses. *BMJ*, 327(7414), 557–560. Available from: https://doi.org/10.1136/bmj.327.7414.557

Ihsan, M., Watson, G. & Abbiss, C.R. (2016) What are the physiological mechanisms for post-exercise cold water immersion in the recovery from prolonged endurance and intermittent exercise? *Sports Medicine*, 46(8), 1095–1109. Available from: https://doi.org/10.1007/s40279-016-0483-3

IntHout, J., Ioannidis, J.P.A., Rovers, M.M. & Goeman, J.J. (2016) Plea for routinely presenting prediction intervals in meta-analysis. *BMJ Open*, 6(7), e010247. Available from: https://doi.org/10.1136/bmjopen-2015-010247

Jouven, X., Empana, J.P., Schwartz, P.J., Desnos, M., Courbon, D. & Ducimetière, P. (2005) Heart-rate profile during exercise as a predictor of sudden death. *New England Journal of Medicine*, 352(19), 1951–1958. Available from: https://doi.org/10.1056/NEJMoa043012

Kaesaman, N. (2019) The acute effect of traditional Thai massage on recovery from fatigue in basketball players. *International Journal of GEOMATE*, 16(55), 53–58. Available from: https://doi.org/10.21660/2019.55.4656

Kellmann, M. & Beckmann, J. (2017) *Sport, Recovery, and Performance: Interdisciplinary Insights*. London: Taylor & Francis Ltd.

Kellmann, M., Bertollo, M., Bosquet, L., Brink, M., Coutts, A.J., Duffield, R. et al. (2018) Recovery and performance in sport: consensus statement. *International Journal of Sports Physiology and Performance*, 13(2), 240–245. Available from: https://doi.org/10.1123/ijspp.2017-0759

Khan, Z., Ahmad, I. & Hussain, M.E. (2020) Intermittent pneumatic compression changes heart rate recovery and heart rate variability after short term submaximal exercise in collegiate basketball players: a cross-over study. *Sport Sciences for Health*, 17(2), 317–326. https://doi.org/10.1007/s11332-020-00684-w

Kinoshita, T., Nagata, S., Baba, R., Kohmoto, T. & Iwagaki, S. (2006) Cold-water face immersion per se elicits cardiac parasympathetic activity. *Circulation Journal*, 70(6), 773–776.

Laborde, S., Allen, M.S., Borges, U., Dosseville, F., Hosang, T.J., Iskra, M. et al. (2022) Effects of voluntary slow breathing on heart rate and heart rate variability: a systematic review and a meta-analysis. *Neuroscience and Biobehavioral Reviews*, 138, 104711. Available from: https://doi.org/10.1016/j.neubiorev.2022.104711

Laborde, S., Mosley, E. & Mertgen, A. (2018a) A unifying conceptual framework of factors associated to cardiac vagal control. *Heliyon*, 4(12), e01002. Available from: https://doi.org/10.1016/j.heliyon.2018.e01002

Laborde, S., Mosley, E. & Mertgen, A. (2018b) Vagal tank theory: the three Rs of cardiac vagal control functioning – resting, reactivity, and recovery. *Frontiers in Neuroscience*, 12, 458. Available from: https://doi.org/10.3389/fnins.2018.00458

Laborde, S., Mosley, E. & Thayer, J.F. (2017) Heart rate variability and cardiac vagal tone in psychophysiological research - recommendations for experiment planning, data analysis, and data reporting. *Frontiers in Psychology*, 08, 213. Available from: https://doi.org/10.3389/fpsyg.2017.00213

Laborde, S., Zammit, N., Iskra, M., Mosley, E., Borges, U., Allen, M.S. et al. (2022) The influence of breathing techniques on physical sport performance: a systematic review and meta-analysis. *International Review of Sport and Exercise Psychology*, 0, 1–56. Available from: https://doi.org/10.1080/1750984x.2022.2145573

Lakens, D. (2013) Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. *Frontiers in Psychology*, 4, 863. Available from: https://doi.org/10.3389/fpsyg.2013.00863

Larsen, P.D., Tzeng, Y.C., Sin, P.Y. & Galletly, D.C. (2010) Respiratory sinus arrhythmia in conscious humans during spontaneous respiration. *Respiratory Physiology & Neurobiology*, 174(1–2), 111–118. Available from: https://doi.org/10.1016/j.resp.2010.04.021

Leicht, A.S., Ahmadian, M. & Nakamura, F.Y. (2020) Influence of lower body compression garments on cardiovascular autonomic responses prior to, during and following submaximal cycling exercise. *European Journal of Applied Physiology*, 120(7), 1601–1607. Available from: https://doi.org/10.1007/s00421-020-04391-9

L'Hermette, M., Castres, I., Coquart, J., Tabben, M., Ghoul, N., Andrieu, B. et al. (2020) Cold water immersion after a handball training session: the relationship between physical data and sensorial experience. *Frontiers In Sports And Active Living*, 2, 581705. https://doi.org/10.3389/fspor.2020.581705

Lombardi, G., Ziemann, E. & Banfi, G. (2017) Whole-Body cryotherapy in athletes: from therapy to stimulation. An updated review of the literature. *Frontiers in Physiology*, 8, 258. Available from: https://doi.org/10.3389/fphys.2017.00258

Machado, A.F., Ferreira, P.H., Micheletti, J.K., de Almeida, A.C., Lemes, Í.R., Vanderlei, F.M. et al. (2016) Can water temperature and immersion time influence the effect of cold water immersion on muscle soreness? A systematic review and meta-analysis. *Sports Medicine*, 46(4), 503–514. Available from: https://doi.org/10.1007/s40279-015-0431-7

Malik, M., Bigger, J.T., Camm, A.J., Kleiger, R.E., Malliani, A., Moss, A.J. et al. (1996) Heart rate variability: standards of measurement, physiological interpretation, and clinical use. *European Heart Journal*, 17, 354–381.

Michael, S., Graham, K.S. & Davis, G.M. (2017) Cardiac autonomic responses during exercise and post-exercise recovery using heart rate variability and systolic time intervals-a review. *Frontiers in Physiology*, 8, 301. Available from: https://doi.org/10.3389/fphys.2017.00301

Micheletti, J.K., Vanderlei, F.M., Machado, A.F., de Almeida, A.C., Nakamura, F.Y., Netto Junior, J. et al. (2019) A new mathematical approach to explore the post-exercise recovery process and its applicability in a cold water immersion protocol. *The Journal of Strength and Conditioning Research*, 33(5), 1266–1275. https://doi.org/10.1519/JSC.0000000000003041

Mosley, E., Duncan, S., Jones, K., Herklots, H., Kavanagh, E. & Laborde, S. (2023) A smartphone enabled slow-paced breathing intervention in dual career athletes. *Journal of Sport Psychology in Action*, 0, 1–16. Available from: https://doi.org/10.1080/21520704.2023.2194256

Mosley, E. & Laborde, S. (2022) A scoping review of heart rate variability in sport and exercise psychology. *International Review of Sport and Exercise Psychology*, 0, 1–75. Available from: https://doi.org/10.1080/1750984x.2022.2092884

Moyer, C.A., Rounds, J. & Hannum, J.W. (2004) A meta-analysis of massage therapy research. *Psychological Bulletin*, 130(1), 3–18. Available from: https://doi.org/10.1037/0033-2909.130.1.3

de Oliveira Ottone, V., de Castro Magalhães, F., de Paula, F., Avelar, N.C.P., Aguiar, P.F., da Matta Sampaio, P.F. et al. (2014) The effect of different water immersion temperatures on post-exercise parasympathetic reactivation. *PLoS One*, 9(12), e113730. Available from: https://doi.org/10.1371/journal.pone.0113730

Ortiz, Jr., R.O., Sinclair Elder, A.J., Elder, C.L. & Dawes, J.J. (2019) A systematic review on the effectiveness of active recovery interventions on athletic performance of professional-, collegiate-, and competitive-level adult athletes. *Journal of Strength and Conditioning Research*, 33(8), 2275–2287. Available from: https://doi.org/10.1519/JSC.0000000000002589

Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D. et al. (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*, 372, n71. Available from: https://doi.org/10.1136/bmj.n71

Parouty, J., Al Haddad, H., Quod, M., Lepretre, P.M., Ahmaidi, S. & Buchheit, M. (2010) Effect of cold water immersion on 100-m sprint performance in well-trained swimmers. *European Journal of Applied Physiology*, 109(3), 483–490. https://doi.org/10.1007/s00421-010-1381-2

Peake, J.M. (2019) Recovery after exercise: what is the current state of play? *Current Opinion in Physiology*, 10, 17–26. Available from: https://doi.org/10.1016/j.cophys.2019.03.007

Pelka, M., Kölling, S., Ferrauti, A., Meyer, T., Pfeiffer, M. & Kellmann, M. (2017) Acute effects of psychological relaxation techniques between two physical tasks. *Journal of Sports Sciences*, 35(3), 216–223. Available from: https://doi.org/10.1080/02640414.2016.1161208

Penttilä, J., Helminen, A., Jartti, T., Kuusela, T., Huikuri, H.V., Tulppo, M.P. et al. (2001) Time domain, geometrical and frequency domain analysis of cardiac vagal outflow: effects of various respiratory patterns. *Clinical Physiology*, 21(3), 365–376.

Perez-Gaido, M., Lalanza, J.F., Parrado, E. & Capdevila, L. (2021) Can HRV biofeedback improve short-term effort recovery? Implications for intermittent load sports. *Applied Psychophysiology And Biofeedback*, 46(2), 215–226. Available from: https://doi.org/10.1007/s10484-020-09495-8

Peterson, A.R., Smoot, M.K., Erickson, J.L., Mathiasen, R.E., Kregel, K.C. & Hall, M. (2015) Basic recovery aids: what's the evidence? *Current Sports Medicine Reports*, 14(3), 227–234. Available from: https://doi.org/10.1249/JSR.0000000000000159

Piras, A. & Gatta, G. (2017) Evaluation of the effectiveness of compression garments on autonomic nervous system recovery after exercise. *Journal of Strength and Conditioning Research*, 31(6), 1636–1643. Available from: https://doi.org/10.1519/JSC.0000000000001621

Quintana, D.S., Alvares, G.A. & Heathers, J.A.J. (2016) Guidelines for reporting articles on psychiatry and heart rate variability (GRAPH): recommendations to advance research communication. *Translational Psychiatry*, 6, e803. Available from: https://doi.org/10.1038/tp.2016.73

R Development Core Team. (2022) *A language and environment for statistical computing*. Vienna, Austria: EEA.

Sandercock, G.R.H., Bromley, P.D. & Brodie, D.A. (2005) Effects of exercise on heart rate variability: inferences from meta-analysis. *Medicine & Science in Sports & Exercise*, 37(3), 433–439. Available from: https://doi.org/10.1249/01.mss.0000155388.39002.9d

Schaal, K., Le Meur, Y., Bieuzen, F., Petit, O., Hellard, P., Toussaint, J.F. et al. (2013) Effect of recovery mode on postexercise vagal reactivation in elite synchronized swimmers. *Applied Physiology, Nutrition, and Metabolism*, 38(2), 126–133. Available from: https://doi.org/10.1139/apnm-2012-0155

Schmaußer, M., Hoffmann, S., Raab, M. & Laborde, S. (2022) The effects of noninvasive brain stimulation on heart rate and heart rate variability: A systematic review and meta-analysis. *Journal of Neuroscience Research*, 100(9), 1664–1694. Available from: https://doi.org/10.1002/jnr.25062

Seiler, S., Haugen, O. & Kuffel, E. (2007) Autonomic recovery after exercise in trained athletes: intensity and duration effects. *Medicine and Science in Sports and Exercise*, 39(8), 1366–1373. Available from: https://doi.org/10.1249/mss.0b013e318060f17d

Sevoz-Couche, C. & Laborde, S. (2022) Heart rate variability and slow-paced breathing: when coherence meets resonance. *Neuroscience and Biobehavioral Reviews*, 135, 104576. Available from: https://doi.org/10.1016/j.neubiorev.2022.104576

Smith, R., Thayer, J.F., Khalsa, S.S. & Lane, R.D. (2017) The hierarchical basis of neurovisceral integration. *Neuroscience and Biobehavioral Reviews*, 75, 274–296. Available from: https://doi.org/10.1016/j.neubiorev.2017.02.003

Soares, A.H.G., Oliveira, T.P., Cavalcante, B.R., Farah, B.Q., Lima, A.H.R.A., Cucato, G.G. et al. (2017) Effects of active recovery on autonomic and haemodynamic responses after aerobic exercise. *Clinical Physiology and Functional Imaging*, 37(1), 62–67. Available from: https://doi.org/10.1111/cpf.12268

Stanley, J., Buchheit, M. & Peake, J.M. (2012) The effect of post-exercise hydrotherapy on subsequent exercise performance and heart rate variability. *European Journal of Applied Physiology*, 112(3), 951–961. https://doi.org/10.1007/s00421-011-2052-7

Stanley, J., Peake, J.M. & Buchheit, M. (2013a) Consecutive days of cold water immersion: effects on cycling performance and heart rate variability. *European Journal of Applied Physiology*, 113(2), 371–384. https://doi.org/10.1007/s00421-012-2445-2

Stanley, J., Peake, J.M. & Buchheit, M. (2013b) Cardiac parasympathetic reactivation following exercise: implications for training prescription. *Sports Medicine*, 43(12), 1259–1277. Available from: https://doi.org/10.1007/s40279-013-0083-4

Stanley, J., Peake, J.M., Coombes, J.S. & Buchheit, M. (2014) Central and peripheral adjustments during high-intensity exercise following cold water immersion. *European Journal of Applied Physiology*, 114(1), 147–163. https://doi.org/10.1007/s00421-013-2755-z

Stephens, J.M., Halson, S., Miller, J., Slater, G.J. & Askew, C.D. (2017) Cold-Water immersion for athletic recovery: one size does not fit all. *International Journal of Sports Physiology and Performance*, 12(1), 2–9. Available from: https://doi.org/10.1123/ijspp.2016-0095

Sterne, J.A.C., Savović, J., Page, M.J., Elbers, R.G., Blencowe, N.S., Boutron, I. et al. (2019) RoB 2: a revised tool for assessing risk of bias in randomised trials. *BMJ*, 366, l4898. Available from: https://doi.org/10.1136/bmj.l4898

Tacconelli, E. (2010) Systematic reviews: CRD's guidance for undertaking reviews in health care. *The Lancet Infectious Diseases*, 10(4), 226. Available from: https://doi.org/10.1016/s1473-3099(10)70065-7

Thacker, S.B., Gilchrist, J., Stroup, D.F., & Kimsey Jr., CD (2004) The impact of stretching on sports injury risk: a systematic review of the literature. *Medicine and Science in Sports and Exercise*, 36(3), 371–378. Available from: https://doi.org/10.1249/01.mss.0000117134.83018.f7

Thayer, J.F., Hansen, A.L., Saus-Rose, E. & Johnsen, B.H. (2009) Heart rate variability, prefrontal neural function, and cognitive performance: the neurovisceral integration perspective on self-regulation, adaptation, and health. *Annals of Behavioral Medicine*, 37, 141–153. Available from: https://doi.org/10.1007/s12160-009-9101-z

Versey, N.G., Halson, S.L. & Dawson, B.T. (2013) Water immersion recovery for athletes: effect on exercise performance and practical recommendations. *Sports Medicine*, 43(11), 1101–1130. Available from: https://doi.org/10.1007/s40279-013-0063-8

Zhong, H., Eungpinichpong, W., Wang, X., Chatchawan, U., Wanpen, S. & Buranruk, O. (2018) Effects of mechanical-bed massage on exercise-induced back fatigue in athletes. *Journal of Physical Therapy Science*, 30(3), 365–372. Available from: https://doi.org/10.1589/jpts.30.365

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Laborde, S., Wanders, J., Mosley, E. & Javelle, F. (2023) Influence of physical post-exercise recovery techniques on vagally-mediated heart rate variability: a systematic review and meta-analysis. *Clinical Physiology and Functional Imaging*, 1–22. https://doi.org/10.1111/cpf.12855