Sports Medicine - Open

SYSTEMATIC REVIEW Open Access

Exercise and Heart Rate Variability in Chronic Musculoskeletal Pain: A Systematic Review

Timo Meus[1,2*], Julie Van Eetvelde[1,2,3], Iris Meuwissen[1,2,3], Mira Meeus[2,3,4], Daniel Boullosa[5,6,7], Annick Timmermans[1†] and Jonas Verbrugghe[1,2†]

Abstract

Background Chronic musculoskeletal pain (CMP) is a prevalent condition associated with significant disability. Emerging evidence suggests that autonomic dysfunction, reflected by heart rate variability (HRV), may play a role in the pathophysiology of CMP and could be responsive to exercise interventions. This systematic review aims to evaluate the effects of exercise on HRV in persons with CMP.

Methods A comprehensive search was performed in PubMed, Web of Science, and Cochrane databases from database inception until June 15, 2024. Eligible studies included those examining exercise interventions of ≥ four weeks in adults aged 18 to 65 with CMP, where HRV was assessed both before and after the intervention. Non-experimental study designs and studies focusing exclusively on acute exercise effects were excluded. Two independent reviewers performed data extraction and assessed the risk of bias using the Cochrane RoB-2 and ROBINS-I tools. The CERT was used for reporting, and effect sizes for exercise interventions were calculated. Certainty of evidence was assessed using the GRADE framework.

Results Five randomized and five non-randomized controlled trials were included, involving 277 persons with CMP. There was considerable variability in HRV measurement protocols. The exercise interventions, which included resistance, aerobic, and multi-component training, lasted four to 24 weeks. Significant within-group improvements were found in several HRV measures, especially in linear analyses linked to vagal modulation at rest.

Conclusions While evidence suggests the positive influence of exercise on autonomic function in CMP, as indicated by HRV changes, the limited number of high-quality studies warrants cautious interpretation. To better understand the impact of different exercise modalities on HRV and address existing data gaps, future research should implement strict protocols for HRV measurements and consistently adhere to established reporting criteria for exercise interventions.

†Annick Timmermans and Jonas Verbrugghe contributed equally to this work.

*Correspondence:
Timo Meus
timo.meus@uhasselt.be

Full list of author information is available at the end of the article

Key Points

1. Exercise should be rigorously investigated and considered as a therapeutic strategy for enhancing heart rate variability (HRV) in persons with chronic musculoskeletal pain (PwCMP), potentially improving both symptom management and overall clinical outcomes.
2. Although comprehensive standards for HRV measurement, including protocols for data acquisition, processing, and analysis, have been published and endorsed, adherence in research practice remains inconsistent. Future studies should prioritize not only adoption but also transparent use to ensure data reliability, reproducibility, and comparability across studies. This will enhance the robustness of conclusions regarding the effects of exercise on autonomic function in PwCMP.
3. To advance our understanding of how exercise influences HRV and autonomic function in PwCMP, future research must rigorously adhere to established exercise reporting guidelines, such as the Consensus on Exercise Reporting Template (CERT).

Keywords Chronic musculoskeletal pain, Autonomic function, Heart rate variability, Vagal modulation, Parasympathetic activity

Background

Chronic musculoskeletal pain (CMP) represents a major global health challenge. It exerts a significant burden on public health systems and contributes substantially to disability worldwide [1–3]. Predictions suggest an exponential increase in CMP's prevalence and socioeconomic burden, underscoring the urgent need for effective interventions to mitigate its impact on healthcare systems, quality of life, and global economic costs [4].

The intricate pathophysiology of CMP underscores its multifactorial nature, implicating a complex interplay of physiological, psychological, and social factors in both its onset and evolution [5–7]. Recent research has shown a clear association between CMP and autonomic function, referring to the involuntary regulation and control of bodily functions, including heart rate (HR). These functions are crucial for maintaining optimal physiological function and facilitating adaptation to environmental changes [8–10]. Thus, elucidating the relationship between CMP and autonomic control is vital for advancing our understanding of this complex condition.

Evidence has demonstrated a clear relationship between CMP and alterations in brain activity, particularly an upsurge in the activation of cognitive-emotional neural networks such as the amygdala and prefrontal cortex [11–13]. Importantly, these brain regions are closely linked to autonomic regulation through central autonomic pathways, including the vagus nerve, which serves as a major conduit between the brain and the autonomic nervous system [14]. In persons with CMP (PwCMP), interactions between these brain regions and autonomic function, specifically HRV (i.e., widely recognized as a non-invasive marker of cardiac autonomic nervous system function reflecting the variation in time intervals between consecutive heartbeats [15]), have been observed, suggesting that vagally mediated HRV may be a key marker of organism adaptability and health in this population [14, 16, 17]. These findings indicate that HRV captures essential organism functions (i.e., autonomic flexibility, homeostatic regulation) associated with overall health and adaptability in PwCMP, highlighting the role of the vagus nerve in connecting neural and autonomic processes. In fact, according to most clinical trials [14, 18, 19], chronic pain relates to a reduction in HRV, which primarily reflects decreased parasympathetic (vagal) modulation. While reduced HRV has sometimes been interpreted as a shift toward sympathetic dominance related to endogenous pain modulation [20], it is important to note that HRV is not a direct measure of sympathetic nervous system activity [21]. Ultimately, HRV represents a relevant factor in chronic pain follow-up [22], as these findings highlight the complex relationship between the autonomic nervous system and pain regulation [10, 23, 24].

Physical activity (PA) and exercise (i.e., structured PA) are currently considered primary therapeutic options for CMP due to their efficacy in improving pain and disability, affordability, and safety profile without the adverse effects commonly associated with pharmacological interventions or invasive procedures [25, 26]. Studies provide compelling evidence supporting the beneficial effects of various exercise modalities, including aerobic, resistance, and multi-component exercise (i.e., mind-body, flexibility, and combined aerobic and resistance exercises), on cardiac autonomic functioning, as evidenced by increased HRV in healthy individuals [27–29] and PwCMP (i.e., neck and low back pain) [10, 30].

Despite these benefits, the effects of various exercise modalities on cardiac autonomic functioning require further clarification, with particular emphasis on the potential mediating role of exercise mode and dosage in modulating HRV outcomes. For instance, aerobic exercise predominantly enhances cardiac autonomic function among healthy adults, yet resistance training, when appropriately dosed in frequency and intensity, can

similarly enhance HRV [27, 31]. However, current evidence [32] supports the superiority of high-intensity training (HIT) in improving HRV in healthy people and athletes, necessitating further investigation to determine if this also applies to PwCMP.

Thus, there is an urgent need for more comprehensive data regarding the effects of various exercise modalities and their dosage on HRV parameters within this population to design more efficient exercise interventions. Therefore, the primary objective of this review was to thoroughly investigate and analyze the impact of different exercise modalities on HRV in PwCMP. In line with this aim, the hypothesis of this systematic review was that structured PA and specific exercise modalities positively influence HRV in PwCMP, potentially improving autonomic function and contributing to pain modulation.

Methods

This review was registered in the international Prospective Register of Systematic Reviews (CRD42024542629) and performed following the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines (see Appendix I) [33].

Eligibility Criteria

Inclusion and exclusion criteria are listed in Table 1.

Search Strategy and Information Sources

Searches were performed on the following electronic databases: PubMed, Scopus, Web of Science, and Cochrane Library from database inception until June 15, 2024. Search terms were tailored for each database, and no limitations were applied regarding publication date or language. Two authors (T.M. and J.V.E.) conducted the screening and literature search, with the search strategy details provided in Appendix II.

Selection Process

Search results were exported, organized, and de-duplicated within EndNote [34] and Rayyan [35]. Two independent reviewers (T.M. and J.V.E.) selected the studies based on the eligibility criteria. First, articles were considered based on title and abstract, and when potentially compliant with eligibility criteria, chosen to be read in full. Disagreements between the reviewers (T.M. and J.V.E.) were resolved through discussion or by the opinion of a third reviewer (I.M.).

Data Collection Process and Data Items

The data from each study were separately extracted and categorized in an agreed-upon template by both researchers (T.M. and J.V.E.). First, an overview table with study characteristics as the reference, the year of publication, the study design, and participant characteristics (age, sex, body mass index (BMI), symptom duration, pain intensity, and clinical diagnosis) was set up. Second, HRV measures (device specifications, instructions, body positioning, HRV indexes, data collection duration, and prerequisite conditions) were extracted. Last, intervention details were categorized based on the recognized consensus on exercise reporting template (CERT), which features seven categories: information regarding the materials, provider, delivery, location, dosage, tailoring, and planning [36]. Where means and SDs were not provided, the respective authors of the articles were contacted by e-mail to request the missing data. If no data were received within eight weeks, the articles were excluded from the analysis, and no effect sizes were calculated.

Study Risk of Bias Assessment

Two independent researchers (T.M. and J.V.E.) utilized the Cochrane risk-of-bias tool for randomized trials (RoB-2 tool) [37] and Cochrane risk-of-bias in non-randomized studies (ROBINS-I) tool [38] to determine

Table 1 Inclusion and exclusion criteria for study selection

Criteria	Description
Inclusion criteria	1. Studies primarily including persons with CMP, which is persistent or recurring and lasting more than three months
	2. Studies including participants aged between 18 and 65 years
	3. Studies involving active exercise interventions, where participants engage in endurance training, resistance training, coordinative exercise, or multimodal exercise.
	3.1. Studies with minimum intervention duration of four weeks, including at least two exercise sessions per week
	4. Studies using HRV as an outcome measure and employing HRV measures derived from linear (time- and frequency-domain) and/or non-linear analyses, with at least one resting measurement taken before and after the intervention
Exclusion criteria	1. Studies involving participants with known cardiovascular, respiratory, infectious, metabolic, neurological, autoimmune, or cancerous diseases
	2. Studies including combination therapies with passive interventions
	3. Studies measuring the effects of an acute bout of exercise on HRV, not embedded in an exercise regimen with follow-up
	4. Studies not designed as comparative experimental research such as (randomized) controlled trials, pragmatic trials or quasi-experimental trials.

Abbreviations: CMP, chronic musculoskeletal pain; HRV, heart rate variability

the risk of bias per outcome. The RoB-2 tool assesses various domains, including the randomization process, deviations from intended interventions, missing data, measurement of the outcome, and selection of the reported result, supporting the critical evaluation of randomized controlled trials (RCTs) by identifying potential biases that could impact study validity. The ROBINS-I tool is tailored for assessing bias in non-randomized studies of interventions, evaluating domains such as confounding sources, participant selection, intervention classification, deviations from intended interventions, missing data, outcome measurement, and selection of the reported result. It offers a structured approach for assessing bias in observational, quasi-experimental, and other non-randomized study designs, facilitating a thorough evaluation of bias. Both authors (T.M. and J.V.E.) compared the results, resolving disagreements or conflicts through discussion or seeking a third opinion (I.M.). To quantify agreement between reviewers, interrater reliability was calculated using Cohen's kappa statistic. Risk-of-bias assessments were categorized as low, moderate, or serious risk-of-bias. Low risk indicated reliable findings, moderate suggested some concerns, and serious denoted significant methodological flaws.

Synthesis Methods and Effect Measures

Data synthesis and analysis for this review involved qualitative and quantitative statistical techniques using JMP® Version 16 (SAS Institute Inc., 1989–2024) to clarify the impact of exercise on HRV outcomes. Given the heterogeneous nature of HRV measures, both linear and non-linear HRV measures were utilized to allow for a comprehensive assessment of autonomic functioning. To evaluate the effect of exercise on HRV within the CMP groups, mean values, and SDs from each group (pre- and post-exercise) were utilized to compute the standardized mean difference (SMD). The SMD for HRV measures was determined using Cohen's d, employing the pooled standard deviation from pre- and post-exercise assessments (Cohen's $d_{rm,\ pooled}$) [39]. An intercorrelation coefficient of 0.5 was used to standardize the correction due to missing data. Results from studies were excluded from the quantitative analysis if the mean and SD were not reported. Effect size interpretations adhered to Cohen's benchmarks, where an SMD of 0.20 indicates a small effect, 0.50 is a moderate effect, and ≥ 0.80 is a large effect, following established references [39, 40]. The threshold for statistical significance was set at $\alpha = 0.05$.

Certainty Assessment

The Grading of Recommendations Assessment, Development, and Evaluation (GRADE) approach was used to assess and update the certainty of the evidence, ranging from very low (⨁◯◯◯) to high (⨁⨁⨁⨁) [41, 42]. Evidence from RCTs started at high certainty, whereas evidence from NRCTs started at low certainty. Certainty of the evidence was downgraded by one level based on the following criteria: [1] risk of bias (reported from low to high risk) [37, 38]; [2] inconsistency (results were considered consistent when > 50% of the studies observed a significant difference in the same direction) [43]; [3] indirectness (lack of direct comparison of the intervention in the population of interest) [44]; [4] imprecision (< 400 participants included in the studies, the width of the confidence interval, and whether it excludes a clinically unimportant effect) [45]; [5] publication bias (e.g., studies funded by industry) [46].

Results

Study Selection

The study selection process is illustrated in Fig. 1 [47]. A total of 3,538 potential articles were initially identified through the search process. After removing duplicates, 2,911 studies remained. Based on screening titles and abstracts, 18 articles were selected for full-text reading.

After assessing the full texts, ten articles met the eligibility criteria and were included in the final review; five were non-randomized controlled trials (NRCTs), and five were RCTs.

Risk of Bias in Studies

An overview of the risk of bias assessment using the RoB-2 and ROBINS-I tools is presented in Appendix III-VI. The two reviewers agreed on 52 out of 60 items, yielding a Kappa score of 0.80, confirming substantial agreement [48]. The studies included in this review had an overall risk of bias categorized as 'some concerns' ($N = 9$) or 'serious concerns' ($N = 1$). For five RCTs, the 'some concerns' judgments were attributed to bias arising from the randomization process [49], bias due to deviations from the intended interventions [10, 49, 50], and bias due to missing data [51, 52]. In the case of NRCTs, 'some concerns' or 'serious concerns' were identified in the domains of bias due to confounding [53], bias in the selection of participants [53–55], bias due to deviations from intended interventions [53], bias due to missing data [53, 54, 56, 57], and bias in the measurement of outcomes [57]. Overall, the risk of bias was assessed as low to moderate for all included studies except one, which was deemed to have a serious risk of bias [53].

Study Characteristics

Table 2 provides a comprehensive overview of patient characteristics. The included studies, conducted between 2008 and 2022, encompassed 277 PwCMP, comprising 7.2% males and 92.8% females, with a mean age ranging from 34.6 to 55 years. PwCMP were diagnosed with either fibromyalgia (FM) ($N = 8$; 65.7%) [49–52, 54–57] or

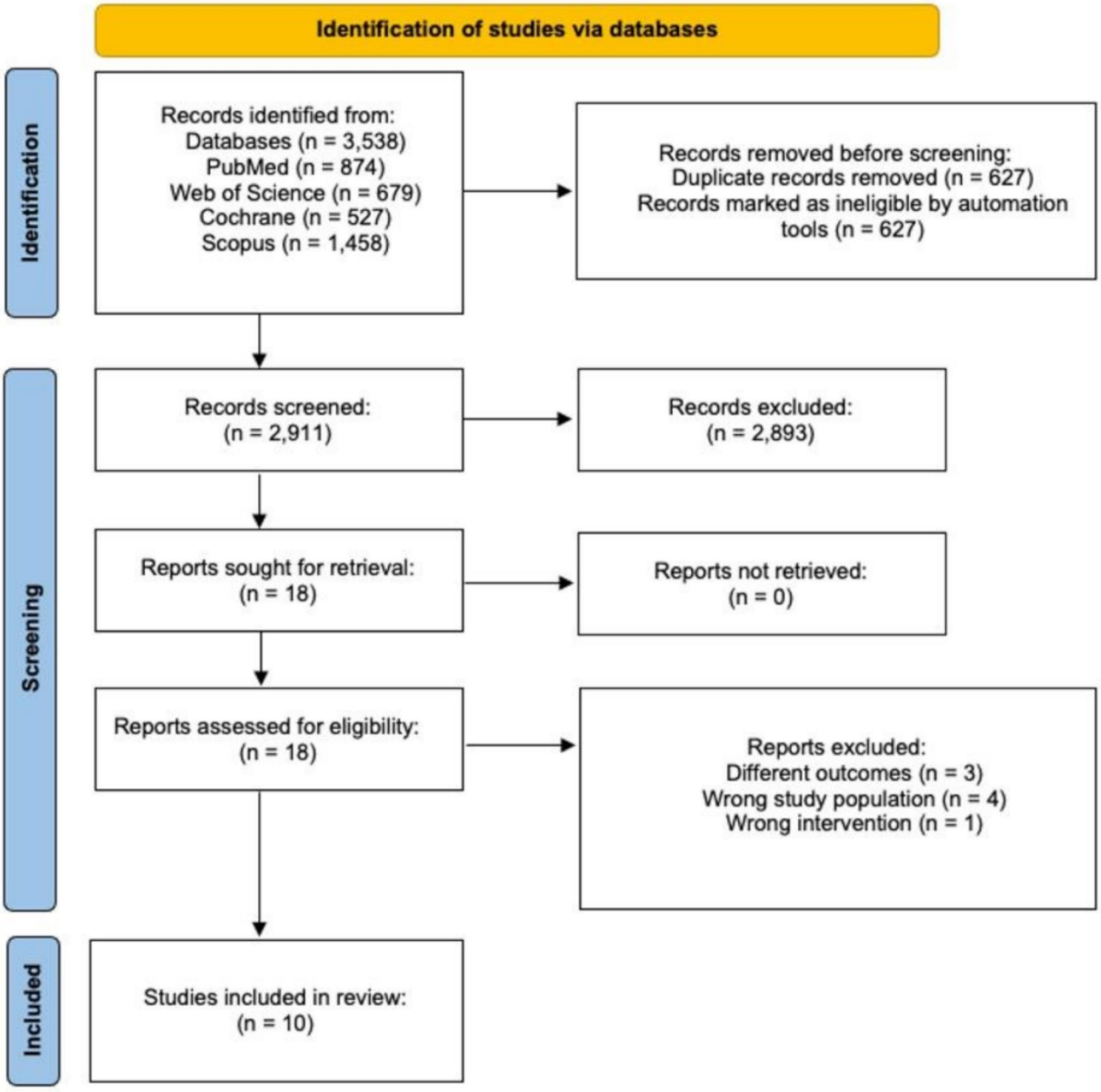

Fig. 1 PRISMA study identification and selection flow chart

chronic low back pain (CLBP) ($N = 2$; 34.3%) [10, 53]. The studies spanned several countries, including the United States [50, 54, 55], Brazil [51, 57], Spain [49, 52, 53], India [10], and Norway [56]. None of the studies provided information regarding the ethnicity of the participants.

Results of Individual Studies

HRV Analyses

An overview of the HRV characteristics is summarized in Table 3. Within the reviewed studies, HRV measurements were conducted via a HR monitor [49, 52, 57] or electrocardiogram (ECG) [10, 50, 51, 53–56] with participants in supine [50–52, 54, 56, 57] or seated [10, 49, 55] positions. The duration of the data collection spanned from five to 30 min across all studies. HRV assessments were conducted under various controlled laboratory conditions, including (1) ambient temperature [10, 49–52, 54, 56, 57], (2) time of day [10, 49, 52, 55, 57], (3) humidity [57], (4) ambient noise levels [10, 50–52, 56], and (5) lighting conditions [56].

Before HRV assessments, participants received instructions regarding [1] beverage consumption [2, 10, 52, 54, 55, 57] food intake [3, 52, 54, 55, 57] alcohol consumption [4, 10, 54, 57] PA levels [5, 52, 54, 55, 57] lifestyle

Table 2 Demographic and clinical characteristics

Study	Age: y (mean ± SD), Sex: *n* (F/M)	BMI: Kg/m^2 (mean ± SD)	Pain duration: y (mean ± SD)	Pain intensity (VAS) (mean ± SD), Clinical diagnosis
Zamunér et al. (2015) [57]	48.0 ± 7.0, 20/0	24.7 ± 3.0	8.0 ± 4.6	NR (FM)
Wong et al. (2018) [50]	51.0 ± 2.0, 17/0	23.1 ± 0.5	8.0 ± 1.0	7.5 ± 0.4 (FM)
Villafaina et al. (2020) [49]	54.0 ± 10.0, 28/0	NR	NR	NR (FM)
Telles et al. (2016) [10]	34.6 ± 6.5, 12/10	NR	NR	NR (CLBP)
Sitges et al. (2022) [53]	45.0 ± 9.1, 13/10	NR	8.1 ± 8.7	8.8 ± 5.9 (CLBP)
Sañudo et al. (2015) [52]	55.0 ± 2.0, 16/0	29.6 ± 1.1	NR	7.4 ± 2.2 (FM)
Kingsley et al. (2010) [55]	42.0 ± 5.0, 9/0	30.4 ± 3.4	7 ± 3	NR (FM)
Gavi et al. (2014) [51]	44.3 ± 7.9, 35/0	NR	NR	7.81 ± 1.59 (FM)
Figueroa et al. (2008) [54]	50.0 ± 10.0, 10/0	29.2 ± 5.8	NR	NR (FM)
Bardal et al. (2015) [56]	54.0 ± 7.3, 16/0	28.1 ± 3.4	8.3 ± 6.5	NR (FM)

Abbreviations: USA, United States of America; n, number of participants; SD, standard deviation; BMI, body mass index; NR, not reported; FM, fibromyalgia; CLBP, chronic low back pain; y, years; F/M, female/male; VAS, visual analogue scale

modifications [6, 50, 55] menstrual cycle considerations [50], and [7] medication usage [54, 55]. During the HRV assessments, guidelines were provided concerning [1] breathing patterns [2, 10] sleep status [3, 56] verbal communication [57], and [4] physical movement [57]. One study [53] did not report on specific instructions, data collection duration, participant positioning, or prerequisite conditions.

HRV Measures

Table 4 provides an overview of how the analysis of HRV is divided into linear and non-linear methods. Linear analysis includes time-domain measures such as the time between two R-wave peaks (RR), root mean square of successive differences (RMSSD), and standard deviation of normal to normal intervals (SDNN), predominantly reflecting parasympathetic (vagal) modulation, and frequency-domain measures such as very low-frequency (VLF), low-frequency (LF) power, and LF to high-frequency (LF/HF) ratio which further differentiate autonomic influences, and assess the power and distribution of these intervals across different frequencies [15, 58]. Non-linear methods, on the other hand, evaluate the complexity and unpredictability of HRV, providing deeper insights into cardiac autonomic function. Importantly, there are major limitations when using frequency-domain methods of HRV (VLF, LF, and LF/HF specifically), as their physiological interpretation remains controversial and context-dependent [59, 60]. This context is essential for interpreting HRV findings, as it highlights which indices are most closely associated with sympathetic or parasympathetic activity and informs the reader before delving into the actual results, where two studies incorporated linear and non-linear analysis [49, 57], while eight focused exclusively on linear analysis of HRV [10, 50–56].

Exercise Intervention Characteristics

A comprehensive overview of the intervention characteristics is detailed in Table 5. The interventions encompassed a total duration ranging from four [53] to 24 [52] weeks. These interventions were diverse and classified as resistance [51, 54, 55], aerobic [52, 56], or multi-component training [10, 49, 53, 57, 61].

Resistance training targeted upper- and lower-limb exercises, with an overall volume of two to three sessions per week and included volumes ranging from one set of eight to three sets of twelve repetitions. Exercise intensity varied from 45 to 85% of the one-repetition maximum (1RM) [51, 54, 55].

Aerobic training comprised steady-state exercises and interval training, with a frequency of two sessions per week. Target exercise intensities were defined as between the first and second ventilatory thresholds [56] or 60–80% of the predicted maximum HR (HRmax) [52].

Multi-component interventions included a diverse combination of exercise types: [1] pool exercises combining aerobic and resistance training, performed twice weekly at 50 to 80% of HRmax [2, 57] Tai-chi exercises three times per week, at 40 to 50% of the HR reserve (HRR) [3, 50] exergames focusing on postural control, aerobic, mobility, and coordination exercises, held twice weekly without specified exercise intensity [4, 49] yoga exercises incorporating specific postures and relaxation exercises, conducted twice weekly without prescribed exercise intensity [10], and [5] a technology-supported exercise intervention featuring pain education alongside a 50-minute exercise regimen that included strength, mobility, motor control, relaxation, and self-massage exercises [53].

Results of Syntheses and Certainty of Evidence

HRV and Exercise

Table 6 provides a comprehensive overview of the pre-post effects of long-term exercise regimens on HRV, with

Table 3 Heart rate variability characteristics

Study	HRV measures	Device specifications	Participant Instructions	Positioning	Data collection duration	Prerequisite conditions
Zamunér et al. (2015), Brazil [57]	Mean of RR, Variance of RR, LF, HF, LF/HF ratio, SE, CI, 0 V, 1 V, 2LV, 2UV	HRM (Polar Advanced RS800CX, Polar Electro Co Ltd.)	No caffeine (24 h) No alcohol (24 h No soft drinks (24 h) Meal consumption (2 h before) No strenuous PA (48 h) No talking or moving (during)	Supine and (active) standing	15 min (supine and standing)	Lab T (22 °C) Data collection time: 8:00–12:00 a.m. Air humidity (40–60%)
Wong et al. (2018), USA [50]	LF, HF, LF/HF, TP	ECG (SA-2000E model, Medicore, Korea, SA-2000E)	No altering of lifestyle and regular habits	Supine	5 min	Lab T (23 ± 1 °C) No noise Early- mid follicular phase (during)
Villafaina et al. (2020), Spain [49]	SDNN, RMSDD, SD1, SD2, SD1/SD2	HRM (Polar Advanced RS800CX, Polar Electro Co Ltd.)	"Task force recommendations and instructions were followed" (15)	Sitting	5 min	"Task force recommendations and instructions were followed" (15)
Telles et al. (2016), India [10]	LF, HF, LF/HF ratio, mean of RR, RMSSD, NN50, pNN50	ECG (MP45 data acquisition system, BIOPAC system inc, U.S.A.)	No caffeine (24 h) No alcohol (24 h) Normal breathing (during)	Sitting	5 min	Data collection time: 10:30 a.m. – 12:30 p.m. and 3:30–5:30 p.m. No noise Air-conditioned lab
Sitges et al. (2022), Spain [53]	SDNN, RMSSD, VLF, LF, HF	ECG (QuickAmp amplifier, Brain Products GmbH)	NR	NR	NR	NR
Sañudo et al. (2015), Spain [52]	LnTP, LnLF, LnHF, LnLF/HF, LnrMSSD, LFnu, HF nu, LF/HF nu	HRM (omegawave sport technology system, Eugene, OR)	No caffeine (12–24 h) No food consumption (10–12 h) No moderate to strenuous PA (12–24 h)	Supine	10 min	Lab T (23 °C) Data collection time: 9:30–11:30 a.m. No noise
Kingsley et al. (2010), USA [55]	LnTP, LnLF, LnHF, LnLF/HF ratio	ECG (modified CM5 configuration, Biopac data acquisition system)	No caffeine (12 h) No food consumption (12 h) No strenuous PA (24 h) No medication (24 h) No altering of lifestyle and regular habits	Sitting	5 min	Data collection time: same time of day for repeated measures
Gavi et al. (2014), Brazil [51]	TP, pNN50, RMSSD, LF, H, LFnu, HFnu, LF/HF ratio	ECG (digital electrocardiograph, Micromed)	NR	Supine	10 min	Lab T (22–24 °C) No noise
Figueroa et al. (2008), USA [54]	TP, RMSSD, LF, HF, LF/HF ratio	ECG (modified CM5 lead, Biopac, Santa Barbara, CA, USA)	No caffeine (12 h) No alcohol (12 h) No food consumption (overnight) No medication (12 h) No strenuous PA (24 h)	Supine	5 min	Lab T (25 °C) Same conditions for repeated measures

Table 3 (continued)

Study	HRV measures	Device specifications	Participant Instructions	Positioning	Data collection duration	Prerequisite conditions
Bardal et al. (2015), Norway [56]	SDNN, RMSSD, LF/HF ratio	ECG (Delys Myomonitor IV, Boston, USA)	No sleeping (during)	Supine	30 min	Lab T (23 °C) No noise Dimmed lights

HRV measures are listed as reported by each study. When applicable, units or transformations are indicated: "nu" for normalized units, "Ln" for natural logarithm. Measures without these abbreviations (e.g., LF, HF) are typically in absolute units (ms^2). Abbreviations: ECG, electrocardiogram; HRV, heart rate variability; T, temperature; h, hours; HRM, heart rate monitor; PA, physical activity; TP, total power; LF, low frequency power; HF, high frequency power; LF/HF, ratio of LF-to-HF power; OV, patterns with no variations; 1 V, patterns with one variation; 2LV, patterns with two like variations; 2UV, patterns with two unlike variations; SE, Shannon entropy; CI, complexity index; SDNN, standard deviation of NN intervals; RMSSD, root mean square of successive differences; SD1, poincaré plot standard deviation perpendicular to the line of identity; SD2, Poincaré plot standard deviation along the line of identity; SD1/SD2, ratio of SD1-to-SD2; NN50, successive RR-intervals that differ by more than 50 ms; pNN50, percentage of successive RR-intervals that differ by more than 50 ms; VLF, very low frequency power; Ln, natural logarithm expression; nu, normal units expression

the summarized findings detailed in Table 7. Because measures such as RMSSD and HF are most strongly associated with parasympathetic nervous system (PNS) activity, particular attention was paid to these indices when interpreting the effects of exercise.

HRV and Resistance Training Three studies [51, 54, 55] investigated the effects of resistance training on linear HRV analysis in both time and frequency-domains in persons with FM before and after the training period. One study [54], which followed a 16-week resistance training regimen, reported a significant increase in total power (TP) from 869.00 (± 768.00) to 1256.00 (± 938.00), with a small effect size of 0.45 (95% CI -0.44 to 1.34). Importantly, the natural logarithm of HF power (LnHF), a key marker of PNS activity, also increased from 5.10 (± 1.60) to 5.64 (± 1.87), yielding a small effect size of 0.31 (95% CI -0.57 to 1.19). In the time-domain analysis, the natural logarithm of the RMSSD (LnRMSSD), another robust indicator of PNS modulation, increased from 2.90 (± 0.80) to 3.08 (± 0.88), with a small effect size of 0.21 (95% CI -0.67 to 1.09).

These increases in both HF and RMSSD suggest a trend toward enhanced parasympathetic activity following resistance training. However, two other studies [51, 55] reported no significant changes in HRV parameters, including those most closely related to PNS activity, after 12 to 16 weeks of resistance training. *The certainty of evidence for this cluster was very low and conflicting, mainly due to some concerns about the risk of bias assessments, imprecision, and the inconsistency of the results.*

HRV and Aerobic Training Two studies [52, 56] investigated the effects of aerobic training on HRV in persons with FM before and after the training period. In one study [52], a 24-week intervention involving aerobic steady-state and interval training revealed notable changes in the frequency-domain analysis of HRV. The LnTP increased from 4.80 (± 0.20) to 5.20 (± 0.20), showing a large effect size of 2.00 (95% CI 1.15–2.85). Likewise, LnLF rose from 3.90 (± 0.20) to 4.40 (± 0.30) with a large effect size of 1.89 (95% CI 0.97–2.82). Of particular interest, the LnHF increased from 3.10 (± 0.20) to 3.80 (± 0.20), with a large effect size of 3.50 (95% CI 2.40–4.60), and HF normalized unit (HFnu) also increased from 30.80 (± 12.90) to 36.90 (± 14.80), exhibiting a small effect size of 0.44 (95% CI -0.27–1.14), both reflecting greater PNS activity. In the time-domain analysis, LnRMMSD increased from 2.70 (± 0.10) to 2.90 (± 0.10) with a large effect estimate of 2.00 (95% CI 1.15–2.85), further supporting improved parasympathetic modulation.

A significant decrease, characterized by a large effect size, was reported in the LnLF/HF ratio, which shifted from 1.30 (± 0.10) to 1.10 (± 0.10), reflecting a large effect

Table 4 Overview of the HRV measures used

Study	Linear analysis: TD					Linear analysis: FD				Non-linear analysis				
	μ RR	Var. of RR	RMSSD	SDNN	(p)NN50	VLF	LF	HF	LF/HF	TP	PLV	SE	CI	SD1	SD2	SD1/SD2
Zamunér et al. (2015) [57]	X	X					X	X	X		X	X	X			
Wong et al. (2018) [50]							X	X	X	X						
Villafaina et al. (2020) [49]			X	X										X	X	X
Telles et al. (2016) [10]	X		X		X		X	X	X							
Sitges et al. (2022) [53]			X	X		X	X	X								
Sañudo et al. (2015) [52]			X				X	X	X	X						
Kingsley et al. (2010) [55]							X	X	X	X						
Gavi et al. (2014) [51]			X		X		X	X	X	X						
Figueroa et al. (2008) [54]			X				X	X	X	X						
Bardal et al. (2015) [56]			X	X					X							
Total	2	1	7	3	2	1	8	8	8	5	1	1	1	1	1	1

Abbreviations: HRV, heart rate variability; TP, total power; LF, low frequency power; HF, high frequency power; LF/HF, ratio of LF-to-HF power; PLV, pattern like variations; SE, Shannon entropy; CI, complexity index; SDNN, standard deviation of NN intervals; RMSSD, root mean square of successive differences; SD1, Poincaré plot standard deviation perpendicular to the line of identity; SD2, Poincaré plot standard deviation along the line of identity; SD1/SD2, ratio of SD1-to-SD2; NN50, successive RR-intervals that differ by more than 50 ms; pNN50, percentage of successive RR-intervals that differ by more than 50 ms; FD, frequency-domain; TD, time-domain; Var., Variance

estimate of -2.00 (95% CI -2.85 - -1.15). LFnu decreased from 69.20 (± 12.80) to 59.80 (± 14.70), with a small effect estimate of -0.68 (95% CI -1.40–0.04). Similarly, LF/HFnu reduced from 2.70 (± 1.40) to 2.00 (± 1.00), with a small effect estimate of -0.56 (95% CI -1.26–0.14). Conversely, in another study [56], a 12-week aerobic interval training intervention showed no significant alterations in the time and frequency-domain analysis of HRV. *The overall certainty for this cluster was judged to be low, primarily due to concerns about the risk of bias, imprecision, and inconsistent results across studies.*

HRV and Multi-Component Training Five studies [10, 49, 50, 53, 57] investigated the effects of multi-component training on HRV analysis in persons with FM and CLBP before and after the training period. Multi-component interventions were particularly notable for their consistent effects on PNS-related HRV measures. For instance, pool exercises, incorporating aerobic, resistance, stretching, and relaxation exercises, changed time-domain HRV analysis. The mean of RR increased from 805.4 (± 23.2) to 872.5 ± 2 (2.3), displaying a large effect size of 2.95 (95% CI 2.06–3.83), while the variance of RR shifted from 475.4 (± 113.2) to 689.0 (± 105.4), with a large effect size of 1.95 (95% CI 1.21–2.70), both of which are associated with greater vagal (parasympathetic) tone [57].

Similarly, app-supported exercise, comprising strength training, postural control exercises, aerobic exercises, mobility drills, and coordination exercises, demonstrated significant increases in the SDNN from 23.59 (± 8.38) to 28.37 (± 13.83), showing a small effect estimate of 0.40 (95% CI -0.16–0.95). SDNN, while reflecting overall HRV, is partly influenced by PNS activity; thus, its increase suggests a shift toward improved autonomic balance and greater vagal modulation. The standard deviation of the Poincaré plot (SD2), another variability measure, also increased from 29.37 (± 9.73) to 35.86 (± 16.36), with a small effect size estimate of 0.46 (95% CI -0.10–1.01) [49].

Yoga-based interventions, which included meditation, relaxation techniques, mild aerobic activity, and controlled breathing, produced changes that further highlight enhanced PNS activity. For example, frequency-domain analysis showed a decrease in LFnu from 57.80 (± 14.20) to 50.80 (± 12.00), showing a small effect size of -0.53 (95% CI -1.13–0.07) and an increase in HFnu from 42.20 (± 14.20) to 49.2 (± 12.00), indicating a moderate effect size of 0.53 (95% CI -0.07–1.13). Because HFnu is strongly linked to parasympathetic activity, this increase indicates meaningful enhancement of PNS activity. In the time-domain, the percentage of successive RR-intervals (pNN50), another marker of vagal tone, increased from 7.75 (± 11.64) to 13.40 (± 13.27), with a small effect size of 0.45 (95% CI -0.15–1.05) [10].

Table 5 Exercise intervention characteristics based on concensus on exercise reporting template (CERT) categories

Study	Materials/location	Provider	Delivery	Intervention type	Dosage	Tailoring
Zamunér et al. (2015), Brazil [57]	Warm pool (30 °C) Gym club: closed (pool) room	Qualified physical therapist	Supervised	Hydrotherapy: resistance/ aerobic exercises	Duration: 45 min	Individual progression: yes
					Period: 16 weeks Frequency: 2X/week Intensity: 50–80% HRpeak	Exercise tailoring: Yes
Wong et al. (2018), USA [50]	NR NR	Trained Tai-chi instructor	Supervised	Tai-chi	Duration: 55 min Period: 12 weeks 3X/week Intensity: 40–50% HRR	NR NR
Villafaina et al. (2020), Spain [49]	VirstualEx-FM program	NA	Supervised	Exergame-based exercises: resistance, postural control, aerobic, mobility, coordination exercises	Duration: 60 min	NR
	University facilities				Period: 24 weeks 2X/week NR	Exercise tailoring: Yes
Telles et al. (2016), India [10]	NR	Trained yoga instructor	Supervised	Yoga: breathing, yoga, relaxation exercises	Duration: 60 min	NR
	NR				Period: 12 weeks 3X/week NR	Exercise tailoring: Yes
Sitges et al. (2022), Spain [53]	Rubber massage ball, foam roller, BackFit app University lab: Room equipped for physical exercise	University supervisor	Supervised	App-supported exercises: resistance, motor control, relaxation, flexibility, self-massage exercises	Duration: 50 min Period: 4 weeks 2X/week NR	NR Exercise tailoring: Yes
Sañudo et al. (2015), Spain [52]	NR	NR	Supervised	Aerobic training: steady-state and interval exercises	Duration: 45–60 min	Individual progression: Yes
	NR				Period: 24 weeks 2X/week Intensity steady- state: 60–65% HRmax (15–20') Intensity interval: 75–80% HRmax (6 × 1.5')	Exercise tailoring: Yes
Kingsley et al. (2010), USA [55]	MedX machines	NR	Supervised	Resistance exercise training	Duration: 30 min	Individual progression: Yes
	NR				Period: 12 weeks 2X/week Intensity: 50–85% of 1RM (3 × 8–12 repetitions)	Exercise tailoring: Yes

Table 5 (continued)

Study	Materials/location	Provider	Delivery	Intervention type	Dosage	Tailoring
Gavi et al. (2014), Brazil [51]	NR	NR	Supervised	Resistance exercise training	Duration: 45 min	Individual progression: Yes
	NR				Period: 16 weeks 2X/week Intensity: 45% of 1RM (1 × 12 repetitions)	Exercise tailoring: Yes
Figueroa et al. (2008), USA [54]	MedX machines	NR	Supervised	Resistance exercise training	Duration: 40 min	Individual progression: Yes
	NR				Period: 16 weeks 2X/week Intensity: 50–80% of 1RM (8–12 repetitions	Exercise tailoring: Yes
Bardal et al. (2015), Norway [56]	NR	NR	Supervised	Aerobic interval training	Duration: 45–60 min	Individual progression: Yes
	NR				Period: 12 weeks 2X/week Intensity interval: Between VT1-VT2 Intensity active rest: below VT1	Exercise tailoring: Yes

Abbreviations: HRpeak, heart rate peak; NR, not recorded; NA, not applicable; HRR, heart rate reserve; HRmax, heart rate max; 1RM, 1 repetition maximum; VT1, first ventilatory threshold; VT2, second ventilatory threshold

Table 6 Effects of exercise on HRV measures in persons with chronic musculoskeletal pain

Study	Disorder	Intervention type	HRV index	Pre, mean ± SD	Post, mean ± SD	Cohen's $D_{RM, pooled}$ [95% CI]
Zamunér et al. (2015) [57]	FM	Hydrotherapy: resistance, aerobic exercise	Linear analysis			
			Mean of RR	805.40 ± 23.20	872.50 ± 22.30*	2.95 [2.06–3.83]
			Variance of RR	475.40 ± 113.20	689.00 ± 105.40*	1.95 [1.21–2.70]
			HF power	89.20 ± 19.10	195.40 ± 46.30*	2.64 [1.27–4.01]
			HFnu	43.00 ± 3.80	59.60 ± 3.40	4.59 [3.45–5.73]
			LF/HF ratio	1.83 ± 0.31	0.82 ± 0.13	-3.75 [-4.69 - -2.80]
			Non-linear analysis: symbolic analysis			
			0 V	22.50 ± 2.90	8.10 ± 1.20	-5.71 [-6.96 - -4.45]
			1 V	48.80 ± 1.30	47.80 ± 1.50	-0.71 [-1.35 - -0.07]
			2LV	10.10 ± 1.10	15.90 ± 1.20	5.03 [3.72–6.34]
			2UV	18.70 ± 2.00	28.30 ± 2.40	4.31 [3.09–5.53]
			SE	3.40 ± 0.10	3.81 ± 0.06	4.70 [3.61–5.76]
			CI	1.01 ± 0.04	1.14 ± 0.04	3.25 [2.31–4.19]
Wong et al. (2018) [50]	FM	Tai-chi	Linear analysis			
			LnTP	6.20 ± 0.30	6.10 ± 0.20	-0.38 [-1.04–0.28]
			nLF	64.90 ± 5.00	55.10 ± 5.20**	-1.94 [-2.74 - -1.15]
			nHF	35.10 ± 5.10	44.80 ± 5.10**	1.90 [1.12–2.69]
			LnLF	4.80 ± 0.20	4.00 ± 0.30	-3.02 [-4.16 - -1.89]
			LnHF	3.80 ± 0.20	4.50 ± 0.30	2.65 [1.61–3.69]
			LnLF/LnHF ratio	1.30 ± 0.10	0.90 ± 0.10	-4.00 [-5.13 - -2.87]
Villafaina et al. (2020) [49]	FM	Exergame-based exercises: resistance, postural control, aerobic, mobility, coordination exercises	Linear analysis			
			SDNN	23.59 ± 8.38	28.37 ± 13.83*	0.40 [-0.16–0.95]
			RMSSD	21.56 ± 11.06	24.28 ± 16.97	0.18 [-0.36–0.73]
			Non-linear analysis			
			SD1	15.27 ± 7.83	17.20 ± 12.01	0.18 [-0.36–0.73]
			SD2	29.37 ± 9.73	35.86 ± 16.36*	0.46 [-0.10–1.01]
			SD1/SD2 ratio	0.52 ± 0.16	0.46 ± 0.17	-0.36 [-0.91–0.19]
			HFD	1.33 ± 0.12	1.34 ± 0.15	0.07 [-0.47–0.62]
Telles et al. (2016) [10]	CLBP	Yoga: breathing, relaxation, yoga exercises	Linear analysis			
			LFnu	57.8 ± 14.20	50.8 ± 12.0*	-0.53 [-1.13–0.07]
			HFnu	42.2 ± 14.20	49.2 ± 12.0*	0.53 [-0.07–1.13]
			LF/HF ratio	1.71 ± 1.24	1.15 ± 1.53	-0.40 [-1.00–0.20]
			Mean of RR	0.76 ± 0.09	0.79 ± 0.10	0.31 [-0.28–0.91]
			RMSSD	56.47 ± 49.44	79.14 ± 50.68	0.45 [-0.15–1.05]
			NN50	28.14 ± 39.13	43.88 ± 38.41	0.41 [-0.19–1.00]
			pNN50	7.75 ± 11.64	13.40 ± 13.27*	0.45 [-0.15–1.05]

Table 6 (continued)

Study	Disorder	Intervention type	HRV index	Pre, mean ± SD	Post, mean ± SD	Cohen's $D_{RM, pooled}$ [95% CI]
Sitges et al. (2022) [53]	CLBP	App-supported exercises: resistance, motor control, relaxation, flexibility, self-massage exercises	Linear analysis (NapLog)			
			SDNN	3.51 ± 0.65	3.62 ± 0.66	0.16 [-0.44–0.75]
			RMSSD	3.42 ± 0.75	3.48 ± 0.89	0.07 [-0.52–0.66]
			VLF	4.03 ± 1.22	4.32 ± 1.22	0.24 [-0.36–0.83]
			LF	6.19 ± 1.40	6.52 ± 1.26	0.25 [-0.35–0.84]
			HF	5.81 ± 1.39	5.84 ± 1.77	0.02 [-0.57–0.61]
Sañudo et al. (2015) [52]	FM	Aerobic exercise training: steady-state, interval exercises	Linear analysis			
			LnTP	4.80 ± 0.20	5.20 ± 0.20**	2.00 [1.15–2.85]
			LnLF	3.90 ± 0.20	4.40 ± 0.30*	1.89 [0.97–2.82]
			LnHF	3.10 ± 0.20	3.80 ± 0.20**	3.50 [2.40–4.60]
			LnLF/HF ratio	1.30 ± 0.10	1.10 ± 0.10**	-2.00 [-2.85 - -1.15]
			LnRMSSD	2.70 ± 0.10	2.90 ± 0.10**	2.00 [1.15–2.85]
			LFnu	69.20 ± 12.80	59.80 ± 14.70**	-0.68 [-1.40–0.04]
			HFnu	30.80 ± 12.90	36.90 ± 14.80**	0.44 [-0.27–1.14]
			LF/HFnu	2.70 ± 1.40	2.00 ± 1.00**	-0.56 [-1.26–0.14]
Kingsley et al. (2010) [55]	FM	Resistance exercise training	Linear analysis			
			LnTP	6.20 ± 0.60	6.60 ± 1.20	0.39 [-0.56–1.33]
			LnLF	4.30 ± 0.90	4.90 ± 1.00	0.63 [-0.39–1.01]
			LnHF	4.90 ± 0.60	5.30 ± 1.00	0.46 [-0.49–1.41]
			LnLF/LnHF ratio	0.93 ± 0.15	0.92 ± 0.19	-0.06 [-0.98–0.87]
Gavi et al. (2015) [51]	FM	Resistance exercise training	Linear analysis			
			TP	4095.81 ± 1723.52	2884.52 ± 1326.38	-0.78 [-1.26 - -0.29]
			pNN50	12.59 ± 2.79	6.66 ± 1.60	-2.45 [-3.03 - -1.86]
			RMSSD	48.40 ± 10.31	39.16 ± 8.62	-0.97 [-1.46 - -0.47]
			LF	1007.37 ± 495.27	788.54 ± 424.70	-0.47 [-0.95–0.01]
			HF	1680.60 ± 797.25	1090.25 ± 574.71	-0.83 [-1.31 - -0.34]
			LFnu	42.80 ± 3.03	43.42 ± 3.53	0.19 [-0.28–0.66]
			HFnu	47.24 ± 2.92	47.83 ± 3.40	0.18 [-0.29–0.66]
			LF/HF ratio	1.36 ± 0.23	1.88 ± 0.56	1.07 [-0.47–1.67]
Figueroa et al. (2008) [54]	FM	Resistance exercise training	Linear analysis			
			Mean of RR	849.00 ± 111.00	NR	NA
			TP	869.00 ± 768.00	1256.00 ± 938.00*	0.45 [-0.44–1.34]
			LnRMSSD	2.90 ± 0.80	3.08 ± 0.88*	0.21 [-0.67–1.09]
			LnLF	4.20 ± 1.20	NR	NA
			LnHF	5.10 ± 1.60	5.64 ± 1.87*	0.31 [-0.574–1.191]
			LF/HF ratio	0.84 ± 0.10	NR	NA

Table 6 (continued)

Study	Disorder	Intervention type	HRV index	Pre, mean ± SD	Post, mean ± SD	Cohen's $D_{RM, pooled}$ [95% CI]
Bardal et al. (2015) [56]	FM	Aerobic exercise training: interval exercises	Linear analysis			
			RMSSD	36.00 ± 17.00	40.00 ± 22.00	0.20 [-0.50–0.90]
			SDNN	54.00 ± 30.00	58.00 ± 30.00	0.13 [-0.60–0.83]
			LF/HF ratio	1.20 ± 0.80	1.40 ± 0.80	0.25 [-0.45–0.95]

Abbreviations: HRV, heart rate variability; CI, confidence interval; SD, standard deviation; NR, not reported; NA, not applicable; Cohen's $d_{RM, Pooled}$, Cohen's d for repeated measures, with pooled standard deviations; RR-interval, time elapsed between two successive R-waves of the QRS complex; HF, high frequency power; LF, lower frequency power; VLF, very low frequency power; TP, total power; LF/HF, ratio of LF-to-HF power; OV, patterns with no variations; 1 V, patterns with one variation; 2LV, patterns with two like variations; 2UV, patterns with two unlike variations; SE, Shannon entropy; CI, Abbreviations: complexity index; RMSSD, root mean square of successive differences; SD1, Poincaré plot standard deviation perpendicular to the line of identity; SD2, Poincaré plot standard deviation along the line of identity; SD1/SD2, ratio of SD1-to-SD2; NN50, successive RR-intervals that differ by more than 50 ms; pNN50, percentage of successive RR-intervals that differ by more than 50 ms; VLF, very low frequency power; Ln, natural logarithm expression; nu, normal units expression. *$p < 0.05$, **$p < 0.01$, significant difference between pre-post exercise measures

Tai-chi exercises, which emphasized slow, controlled movements and breath regulation, also resulted in robust improvements in PNS-related HRV measures. Specifically nLF decreased from 64.9 (± 5.0) to 55.1 (± 5.2) with a large effect size of -1.94 (95% CI -2.74 - -1.15), while nHF, a direct indicator of parasympathetic activity, increased from 35.1 (± 5.1) to 44.8 (± 5.1) with a large effect size of 1.90 (95% CI 1.12–2.69) [50]. These changes point to a pronounced shift toward parasympathetic dominance and improved autonomic regulation. *Despite the consistency in significant changes reported, the certainty of evidence for this cluster was low. This was primarily driven by imprecision and some concerns about the risk of bias. Given these limitations, our confidence in the effect estimates is limited.*

Discussion

The primary objective of this systematic review was to thoroughly evaluate and synthesize the current evidence regarding the effects of different exercise modalities on HRV in PwCMP. By systematically analyzing RCTs and NRCTs, we aimed to determine whether structured exercise interventions, specifically resistance, aerobic, and multi-component regimens, can improve autonomic function, as measured by HRV, in this population. The overall evidence suggests that multi-component regimens improve HRV and autonomic function in persons with FM and CLBP. However, the magnitude and direction of these effects are likely influenced by the specific type of exercise intervention and the characteristics of the studied population. In contrast, definitive conclusions regarding the effects of resistance and aerobic exercise regimens on HRV remain elusive due to the limited data, inconsistent findings, and limited evidence certainty. These findings highlight the need for further high-quality studies to robustly elucidate the effects of exercise interventions on HRV among PwCMP.

Changes in HRV after Exercise

Resistance Training and HRV

The reviewed evidence on resistance training and HRV in CMP populations is inconsistent. For example, Figueroa et al. [54] reported increased PNS-related HRV indices in persons with FM, including LnRMSSD and LnHF, after a 16-week supervised resistance training regimen, suggesting an increase in PNS activity. Conversely, Gavi et al. [51] also observed changes in HRV after a similar 16-week intervention in FM patients. However, these changes reflected a decrease in PNS-related (RMSSD, HF) modulation of HRV.

Several methodological differences may explain these contrasting findings. For instance, Figueroa et al. [54] controlled for medication, PA, and consumption of food, caffeine, and alcohol, while Gavi et al. [51] lacked such

Table 7 GRADE assessment of the different exercise clusters

The effects of different exercise modalities on HRV outcomes									
Exercise modality	**Outcome**	**Study**	***n*** **(design)**	**Certainty of evidence assessed**					**Certainty of evidence (GRADE)**
				Risk of bias	**Inconsistency**	**indirectness**	**Imprecision**	**Publication bias**	
Resistance training exercise	Linear and non-linear analysis	Figueroa et al. (2008) [54] Kingsley et al. (2010) [55] Gavi et al. (2014) [51]	54 (1 RCT + 2 non-RCTs)	Not serious[a]	Serious[b]	None	Serious[c]	None	⨁◯◯◯ Very low
Aerobic training exercise	Linear and non-linear analysis	Bardal et al. (2015) [56] Sañudo et al. (2015) [52]	32 (1 RCT + 1 non-RCT)	Not serious[d]	Serious[e]	None	Serious[f]	None	⨁◯◯◯ Very low
Multi-component exercise	Linear and non-linear analysis	Sitges et al. (2022) [53] Telles et al. (2016) [10] Villafaina et al. (2020) [49] Wong et al. (2018) [50] Zamunér et al. (2015) [57]	110 (3 RCTs + 2 non-RCTs)	Not serious[g]	Not serious[h]	None	Serious[c]	None	⨁⨁◯◯ Low

Abbreviations: GRADE, Grading of Recommendations, Assessment, Development and Evaluation; RCT, randomized controlled trial.

Reasons for downgrading:

[a]Figueroa et al. [54], Gavi et al. [51], and Kingsley et al. [55] scored 'some concerns' in the RoB assessment

[b]Kingsley et al. [55] and Gavi et al. [51] did not show improved HRV outcomes after resistance exercise whereas Figueroa et al. [54] did. Figueroa et al.'s [54] weight was lower due to a small sample size, and hence a 'serious' score was given

[c]All clusters presented with less than 400 total participants, and therefore the scoring was 'serious' for all clusters

[d]Bardal et al. [56] and Sanudo et al. [52] scored 'some concerns' in the RoB assessment

[e]Bardal et al. [56] did not show improved HRV outcomes after aerobic exercise whereas Sanudo et al. [52] did. Both studies have an equal sample size, but overall intervention type differs, and therefore a 'serious' score was still given due to only two studies being presented for this cluster

[f]Sitges et al. [53] scored 'serious concerns' overall whereas all the other studies within this cluster scored 'some concerns', and therefore were considered 'not serious' for the risk of bias cluster assessment

[g]Sitges et al. [53] did not show improved HRV outcomes after multi-component training whereas all the other studies did. The score of 'not serious' therefore represents all studies included in the cluster

Studies included in this table: Figueroa et al. (2008) [54]; Kingsley et al. (2010) [55]; Gavi et al. (2015) [51]; Bardal et al. (2015) [56]; Sanudo et al. (2015) [52]; Sitges et al. (2022) [53]; Telles et al. (2016) [10]; Villafaina et al. (2020) [49]; Wong et al. (2018) [50]; Zamunér et al. (2015) [57]

controls. Neither study standardized breathing during HRV measurement, a critical component given its known influence on HRV outcomes [62].

In contrast to the inconsistent findings observed in PwCMP, evidence from healthy adults indicates that resistance training generally does not significantly alter HRV [63–65]. However, studies involving persons with chronic conditions marked by autonomic dysfunction (i.e., coronary artery disease, chronic heart failure, FM) have reported improvements in autonomic function following resistance training [19, 66, 67]. This discrepancy suggests that the presence of underlying autonomic dysfunction may be a key factor influencing HRV responsiveness to resistance training. Nevertheless, given the heterogeneity in study design, participant characteristics, and training protocols, the overall effect of resistance training in PwCMP remains inconclusive. This inconclusiveness is not entirely consistent with evidence from healthy populations, where null findings are more uniformly observed despite variations in intensity and duration [51, 55]. It is plausible that specific features of resistance training, such as total volume, may modulate autonomic adaptations through effects on aerobic metabolism [68]. However, the volume threshold required to induce such changes has yet to be clearly defined.

Overall, future research should aim to standardize HRV measurement protocols [60, 69], carefully consider population characteristics (including diagnostic criteria), and provide detailed descriptions of resistance training interventions to clarify the relationship between resistance training and HRV in healthy adults and PwCMP.

Aerobic Training and HRV

Evidence on aerobic exercise and HRV in PwCMP is similarly mixed in PwCMP. For instance, Sanudo et al. [52] reported significant changes in HRV, both in frequency (TP, LF, HF, LF/HF ratio) and time-domain (RMSSD) measures, after a 24-week exercise intervention in persons with CLBP. Despite the increase in LF, generally not considered a direct marker of vagal modulation, the elevation in PNS-related indices like RMSSD and HF suggests improved parasympathetic modulation. In contrast, Bardal et al. [56] found no HRV changes following a 12-week interval training in persons with FM. This result may reflect the regimen's insufficient intensity or duration, and differing pathophysiology when comparing both populations.

While aerobic training is generally associated with improved HRV in healthy adults [70–72], findings in PwCMP remain inconsistent. This inconsistency may be partly attributed to methodological limitations in existing studies. For instance, Sanudo et al. [52] did not determine individual metabolic thresholds and provided insufficient reporting of exercise dosage, whereas Bardal et al. [56] employed predominantly moderate-intensity protocols. The generally moderate-intensity and potentially insufficient training load used in both studies may also explain the limited changes observed in HRV. Supported by evidence from healthy adults, where HIT has demonstrated more robust effects on HRV compared to moderate-intensity continuous training [73–76]. Collectively, these findings underscore the need for future research to apply individualized, well-controlled exercise prescriptions in order to better explain the relationship between aerobic training and autonomic function in PwCMP.

Importantly, variability in HRV collection protocols between studies may have further influenced the observed discrepancies. Sanudo et al. [52], for example, did not control for respiratory rate during HRV measurement. In fact, neither study implemented standardized procedures for breathing control, which is known to significantly influence frequency-related HRV outcomes [62]. Additionally, Sanudo et al.'s [52] laboratory conditions were poorly reported or inadequately controlled, introducing further uncertainty into the data. However, they did provide relatively comprehensive documentation of pre-assessment confounders such as caffeine intake, food consumption, and PA. In contrast, Bardal et al. [56] applied more rigorous environmental controls, standardizing factors such as temperature, noise, and lighting, but offered limited reporting on pre-measurement behaviors. These methodological inconsistencies, particularly regarding HRV data acquisition and pre-measurement standardization, underscore the critical need for harmonized research protocols to improve the interpretability and comparability of HRV outcomes in PwCMP.

Multi-Component Training and HRV

Our review suggests that multi-component training interventions, combining aerobic and resistance exercises, significantly enhance the mean and variance of RR-intervals and HF power following a 16-week training regimen in PwCMP [57]. These results align with previous research demonstrating significant improvements in HRV measures like SDNN, coefficient of variation (CV), and HF power in healthy adults following similar training regimens [77, 78]. Collectively, these findings suggest that multi-component training, encompassing aerobic and resistance training components, effectively enhances PNS activity in both healthy adults and those with CMP, making it a promising intervention for improving cardiac autonomic function in PwCMP.

Our findings also show that mind-body exercises, like yoga and Tai-chi, lead to increased PNS activity, reflected in changes in HF and pNN50 in PwCMP [10, 50]. Comparable shifts in HF power have been observed in healthy adults [79–81] and persons with chronic cancer-related pain [29]. These consistent findings across diverse

populations suggest that mind-body exercises effectively improve cardiac autonomic function in individuals with and without CMP.

In contrast, our results show that a four-week app-supported rehabilitation regimen did not change HRV, likely due to the high risk of bias and the intervention's short duration, wherein the minimum effective frequency dose is not yet clearly defined. Still, studies report the benefits of exercise on HRV in healthy adults ranging from two to six weeks, but longer interventions (> 12 weeks) may be more effective [82].

Taken together, the results underscore the potential of multi-component exercise, encompassing aerobic and mind-body modalities, to enhance HRV. However, the low-certainty evidence and limited studies require cautious interpretation, emphasizing the need for well-designed studies to investigate exercise effects on HRV and ensure standardized reporting and implementation of HRV measurements.

HRV Measures Considerations

Given the diverse HRV protocols and measures, a detailed implementation analysis is warranted. Many HRV measures, particularly stationary time and frequency-domain measures, are mathematically and physiologically interrelated [15]. Among these, vagal-related parameters, especially RMSSD and HF power, are extensively used and regarded as the most robust indicators of PNS activity. Based on all HRV indices considered in this review and existing recommendations, RMSSD remains one of the most frequently used parameters and a reliable marker of vagally mediated changes in HRV, making it a crucial tool for assessing vagal influence following exercise interventions [58]. Its sensitivity to parasympathetic activity, responsiveness to exercise, consistency across studies, ease of interpretation, and reliability contribute to its widespread use in research and clinical settings [83, 84]. Still, it remains unclear if including both frequency and time-domain metrics, as in many studies [10, 51–54, 56, 57], improves the diagnosis and interpretation of cardiac autonomic adaptations following exercise.

With regard to non-linear analysis of HRV, such as Poincaré plots employed in PwCMP studies, their interpretative and diagnostic potential remains underutilized and insufficiently validated in clinical practice. These methods, as supported by Tulppo et al. [72], offer complementary insights into cardiac autonomic regulation beyond conventional linear metrics. However, standardization in acquisition and interpretation is lacking, and no significant clinical breakthroughs have been achieved to date [85–87]. Furthermore, it remains possible that complexity measures are inadequate for analyzing biological systems and are too insensitive to detect non-linear changes in RR-intervals of physiological and practical importance. For now, non-linear methods represent promise but lack standardization for implementation. Notably, only two of the ten studies [49, 57] included in this review employed non-linear analysis of HRV, and both consistently integrated it with linear HRV analysis.

A critical consideration in HRV analysis is the duration of recordings and the reliability of outcomes. While short recordings (< 4 min) can reliably capture parasympathetic markers like RMSSD, pNN50, and HF power [88]. However, the robustness of these metrics, particularly in the context of limited data, remains a limitation [89]. Recent reviews emphasize that short recordings may not capture the full spectrum of autonomic activity and may lead to reduced reliability and increased variability of HRV indices, especially and mainly so for frequency-domain measures such as LF power, which generally require at least five-minute recordings [60, 89, 90]. Moreover, the number of data points also impacts the validity of non-linear analyses, which are especially sensitive to recording length and data quality [60, 89].

Equally underexplored are the effects of data preprocessing techniques, such as artifact correction algorithms, filtering strategies, and detrending procedures, on HRV outcomes. These technical factors can introduce significant variability, particularly in short recordings, yet are often insufficiently reported or inconsistently applied across studies [91, 92].

In conclusion, although HRV remains a valuable and non-invasive index of autonomic function, its application continues to be hindered by methodological heterogeneity, limited standardization, and unresolved questions about the validity and reliability of certain metrics. Future research should prioritize adhering to developed, standardized, and evidence-based guidelines that account for these nuances of HRV analysis across different domains (i.e., time, frequency, and non-linear) and optimize its translational potential in both research and clinical settings [15, 93].

Strengths and Limitations of the Review

This systematic review identifies several limitations inherent to the included studies and the present review in examining the effects of exercise on HRV in PwCMP. First, including NRCTs aimed to provide a comprehensive perspective of the existing literature. However, future studies should strive to implement well-designed RCTs when assessing exercise effects on HRV in CMP populations. Second, the heterogeneous exercise protocols and HRV analysis methodologies currently limit the feasibility of a meta-analysis, necessitating a combined qualitative and quantitative approach. Third, the study's sample pool of persons with FM and CLBP restricts generalizability to other chronic pain conditions. Fourth, despite not imposing sex-specific restrictions on the search

strategy, only 7.2% of the 277 participants were male, indicating a notable sex disparity in the literature. To provide more balanced insights, future studies could aim to increase the number of male participants, ensuring applicability across sexes. Lastly, a notable limitation is the small number of included studies, restricting the generalizability and robustness of the findings.

Implications for Practice and Research

This review underscores the potential of various exercise interventions, particularly multi-component exercise, including aerobic, resistance, or mind-body exercises, to enhance HRV in persons with FM and CLBP. However, the optimal exercise modality, protocol, and dose for enhancing HRV remains unclear, requiring further research. Future studies should provide detailed descriptions of exercise protocols, including frequency, volume, intensity, and recovery, to allow replication and a better understanding of exercise's impact on CMP autonomic function. Currently, resting HRV is a benchmark for monitoring changes following exercise interventions [94]. Future research could explore HRV during recovery, orthostatic testing, and responsiveness to physical loading to refine exercise intensity prescriptions [95]. Clarifying these nuances may support the development of personalized exercise prescriptions aimed at improving autonomic function and reducing pain, ultimately informing therapeutic strategies that enhance functional outcomes and long-term health in this population.

Conclusions

The findings of this systematic review suggest that multi-component exercise interventions, particularly those incorporating an aerobic component, may positively influence autonomic function in PwCMP. To advance our understanding of how different exercise modalities affect HRV and to address existing data gaps, future research should adopt already developed, rigorous, standardized checklists and protocols for HRV measurements and consistently adhere to established reporting criteria for exercise interventions.

Abbreviations

1RM	One–Repetition Maximum
BMI	Body Mass Index
CERT	Consensus on Exercise Reporting Template
CLBP	Chronic Low Back Pain
CMP	Chronic Musculoskeletal Pain
CV	Coefficient of Variation
FM	Fibromyalgia
GRADE	Grading of Recommendations, Assessment, Development, and Evaluation
HIT	High–Intensity Training
HF	High–Frequency
HFnu	High–Frequency Normalized Unit
HR	Heart Rate
HRmax	Maximum Heart Rate
HRR	Heart Rate Reserve
HRV	Heart Rate Variability
Kappa	A statistical measure of inter–rater agreement
LF	Low–Frequency
LF/HF	Low–Frequency to High–Frequency ratio
LFnu	Low–Frequency Normalized Unit
LnHF	Natural Logarithm of High–Frequency Power
LnRMSSD	Natural Logarithm of Root Mean Square of Successive Differences
NRCT	Non–Randomized Controlled Trial
pNN50	Percentage of successive RR-intervals that differ by more than 50 ms
PA	Physical Activity
PNS	Parasympathetic Nervous System
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta–Analysis
RCT	Randomized Controlled Trial
ROBINS	I–Risk of Bias in Non–Randomized Studies of Interventions
RoB	2–Risk of Bias 2 Tool
RMSSD	Root Mean Square of Successive Differences
RR	Time Between Two R–wave Peaks
SD2	Standard Deviation of the Poincaré Plot (Non–linear analysis of HRV)
SDNN	Standard Deviation of Normal to Normal Intervals
SMD	Standardized Mean Difference
TP	Total Power
PwCMP	Persons with Chronic Musculoskeletal Pain

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40798-025-00916-8.

Appendix I: Supplemental Digital Content 2

Appendix II: Supplemental Digital Content 3

Appendix III-VI

Acknowledgements

D.B. was supported by Grant RYC2021-031098-I funded by MCIN/AEI/https://doi.org/10.13039/501100011033, by "European Union Next Generation EU/PRTR", and by a productivity research grant PQ1-D (317126/2021-0) by CNPq (Brazil).

Author Contributions

T.M., A.T., J.V., M.M., and D.B. were instrumental in the conception and design of the study, contributing to the development of the search strategies. T.M., J.V.E., and I.M. were responsible for selecting eligible studies, data extraction, quality assessment, evidence certainty evaluation, and comprehensive data synthesis. T.M. took the lead in drafting the initial manuscript. All authors engaged in critical revisions of the manuscript. They collectively reviewed and edited the manuscript, providing valuable insights and final approval of the manuscript. T.M. is designated as the guarantor of the work, taking full responsibility for the overall content, including the integrity of the research and the accuracy of the data presented. All authors read and approved the final manuscript.

Funding

Funding sources are the University of Hasselt, Special Research Fund (BOF) (grant number: BOF23DOC40), and Research Foundation Flanders (FWO_TBM) (project number: T000822N). The funding sponsors had no role in the design of the study, in the collection, analysis, or interpretation of data, in the writing of the manuscript, and in the decision to publish the results.

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethical Approval

Not applicable.

Consent for Publication
Not applicable.

Conflict of Interest
The authors declare that they have no financial or non-financial competing interests related to this work. Specifically, within the past three years, none of the authors have received funding, employment, or personal financial benefit from any organization that could be perceived as influencing the content of this manuscript. None of the authors are affiliated with the journal. Although the authors' expertise aligns with the topic of this review, there are no personal, professional, or institutional interests that could be perceived as imparting bias.

Registration Information
The review was prospectively registered in PROSPERO (registration ID: CRD42024542629).

Author details
[1]Faculty of Rehabilitation Sciences and Physiotherapy – REVAL Research Group, Hasselt University, Wetenschapspark 7, Diepenbeek 3590, Belgium
[2]Faculty of Medicine and Health Sciences, Department of Rehabilitation Sciences and Physiotherapy (REVAKI) – MOVANT Research Group, Antwerp University, Antwerp 2610, Belgium
[3]Pain in Motion International Research Consortium (PiM), www.paininmotion.be, Free University of Brussels, Brussels 1050, Belgium
[4]Faculty of Medicine and Health Sciences, Department of Rehabilitation Sciences and Physiotherapy, Ghent University, Ghent 9000, Belgium
[5]Faculty of Physical Activity and Sports Sciences (FCAFD), University of León, León 24007, Spain
[6]Integrated Institute of Health, Federal University of Mato Grosso do Sul, Campo Grande 13471-410, Brazil
[7]College of Healthcare Sciences, James Cook University, Townsville 4811, Australia

Received: 17 December 2024 / Accepted: 1 September 2025
Published online: 01 October 2025

References

1. Buchbinder R, van Tulder M, Öberg B, et al. Low back pain: a call for action. Lancet. 2018;391(10137):2384–8. https://doi.org/10.1016/s0140-6736(18)30488-4. Epub 20180321.
2. Chen S, Chen M, Wu X, et al. Global, regional and National burden of low back pain 1990–2019: A systematic analysis of the global burden of disease study 2019. J Orthop Translat. 2022;32:49–58. PubMed PMID: 34934626; PubMed Central PMCID: PMC8639804.
3. Shin DW, Shin JI, Koyanagi A, et al. Global, regional, and National neck pain burden in the general population, 1990–2019: an analysis of the global burden of disease study 2019. Front Neurol. 2022;13:955367. PubMed PMID: 36119688; PubMed Central PMCID: PMC9477009.
4. Hartvigsen J, Hancock MJ, Kongsted A et al. What low back pain is and why we need to pay attention. Lancet. 2018;391(10137):2356-67. Epub 20180321. https://doi.org/10.1016/s0140-6736(18)30480-x. PubMed PMID: 29573870.
5. Kazeminasab S, Nejadghaderi SA, Amiri P, et al. Neck pain: global epidemiology, trends and risk factors. BMC Musculoskelet Disord. 2022;23(1):26. https://doi.org/10.1186/s12891-021-04957-4. Epub 20220103.
6. Linton SJ. A review of psychological risk factors in back and neck pain. Spine (Phila Pa 1976). 2000;25(9):1148–56. https://doi.org/10.1097/00007632-200005010-00017. PubMed PMID: 10788861.
7. Shiri R, Falah-Hassani K, Heliövaara M, et al. Risk factors for low back pain: A Population-Based longitudinal study. Arthritis Care Res (Hoboken). 2019;71(2):290–9. https://doi.org/10.1002/acr.23710. PubMed PMID: 30044543.
8. Bandeira PM, Reis FJJ, Sequeira VCC, Chaves ACS, Fernandes O, Arruda-Sanchez T. Heart rate variability in patients with low back pain: a systematic review. Scand J Pain. 2021;21(3):426–33. https://doi.org/10.1515/sjpain-2021-0006. Epub 20210503.
9. Santos-de-Araújo AD, Dibai-Filho AV, Dos Santos SN, et al. Correlation between chronic neck pain and heart rate variability indices at rest: A Cross-sectional study. J Manipulative Physiol Ther. 2019;42(4):219–26. PubMed PMID: 31255310.
10. Telles S, Sharma SK, Gupta RK, Bhardwaj AK, Balkrishna A. Heart rate variability in chronic low back pain patients randomized to yoga or standard care. BMC Complement Altern Med. 2016;16(1):279. https://doi.org/10.1186/s12906-016-1271-1. Epub 20160811.
11. Hashmi JA, Baliki MN, Huang L, et al. Shape shifting pain: chronification of back pain shifts brain representation from nociceptive to emotional circuits. Brain. 2013;136(Pt 9):2751–68. https://doi.org/10.1093/brain/awt211. PubMed PMID: 23983029; PubMed Central PMCID: PMC3754458.
12. Thayer JF, Lane RD. A model of neurovisceral integration in emotion regulation and dysregulation. J Affect Disord. 2000;61(3):201–16. https://doi.org/10.1016/s0165-0327(00)00338-4. PubMed PMID: 11163422.
13. Yang S, Chang MC. Chronic Pain: Structural and Functional Changes in Brain Structures and Associated Negative Affective States. Int J Mol Sci. 2019;20(13). Epub 20190626. https://doi.org/10.3390/ijms20133130. PubMed PMID: 31248061; PubMed Central PMCID: PMC6650904.
14. Koenig J, Loerbroks A, Jarczok MN, Fischer JE, Thayer JF. Chronic pain and heart rate variability in a Cross-Sectional occupational sample: evidence for impaired vagal control. Clin J Pain. 2016;32(3):218–25. https://doi.org/10.1097/ajp.0000000000000242. PubMed PMID: 25924095.
15. Heart rate variability : standards of measurement, physiological interpretation and clinical use. Task force of the European society of cardiology and the North American society of pacing and electrophysiology. Circulation. 1996;93(5):1043–65. PubMed PMID: 8598068.
16. Thayer JF, Ahs F, Fredrikson M, Sollers JJ 3rd, Wager TD. A meta-analysis of heart rate variability and neuroimaging studies: implications for heart rate variability as a marker of stress and health. Neurosci Biobehav Rev. 2012;36(2):747–56. PubMed PMID: 22178086.
17. Thayer JF, Hansen AL, Saus-Rose E, Johnsen BH. Heart rate variability, prefrontal neural function, and cognitive performance: the neurovisceral integration perspective on self-regulation, adaptation, and health. Ann Behav Med. 2009;37(2):141 – 53. Epub 20090508. https://doi.org/10.1007/s12160-009-9101-z. PubMed PMID: 19424767.
18. Forte G, Troisi G, Pazzaglia M, Pascalis V, Casagrande M. Heart Rate Variability and Pain: A Systematic Review. Brain Sci. 2022;12(2). Epub 20220124. https://doi.org/10.3390/brainsci12020153. PubMed PMID: 35203917; PubMed Central PMCID: PMC8870705.
19. Rampazo ÉP, Rehder-Santos P, Catai AM, Liebano RE. Heart rate variability in adults with chronic musculoskeletal pain: A systematic review. Pain Pract. 2024;24(1):211–30. Epub 20230903. https://doi.org/10.1111/papr.13294. PubMed PMID: 37661339.
20. Van Den Houte M, Van Oudenhove L, Van Diest I, et al. Negative affectivity, depression, and resting heart rate variability (HRV) as possible moderators of endogenous pain modulation in functional somatic syndromes. Front Psychol. 2018;9:275. https://doi.org/10.3389/fpsyg.2018.00275. Epub 20180306.
21. Heathers JAJ. Everything hertz: methodological issues in short-term frequency-domain HRV. Front Physiol. 2014;5–2014. https://doi.org/10.3389/fphys.2014.00177
22. Gockel M, Lindholm H, Niemistö L, Hurri H. Perceived disability but not pain is connected with autonomic nervous function among patients with chronic low back pain. J Rehabil Med. 2008;40(5):355–8. https://doi.org/10.2340/16501977-0172. PubMed PMID: 18461260.
23. Tracy LM, Ioannou L, Baker KS, Gibson SJ, Georgiou-Karistianis N, Giummarra MJ. Meta-analytic evidence for decreased heart rate variability in chronic pain implicating parasympathetic nervous system dysregulation. Pain. 2016;157(1):7–29. https://doi.org/10.1097/j.pain.0000000000000360. PubMed PMID: 26431423.
24. Rampazo ÉP, Rehder-Santos P, Catai AM, Liebano RE. Heart rate variability in adults with chronic musculoskeletal pain: A systematic review. Pain Pract. 2024;24(1):211–30. https://doi.org/10.1111/papr.13294
25. Babatunde OO, Jordan JL, Van der Windt DA, Hill JC, Foster NE, Protheroe J. Effective treatment options for musculoskeletal pain in primary care: A systematic overview of current evidence. PLoS ONE. 2017;12(6):e0178621. https://doi.org/10.1371/journal.pone.0178621. Epub 20170622.
26. Searle A, Spink M, Ho A, Chuter V. Exercise interventions for the treatment of chronic low back pain: a systematic review and meta-analysis of randomised controlled trials. Clin Rehabil. 2015;29(12):1155–67. Epub 20150213. https://doi.org/10.1177/0269215515570379. PubMed PMID: 25681408.
27. Grässler B, Thielmann B, Böckelmann I, Hökelmann A. Effects of different exercise interventions on heart rate variability and cardiovascular health factors in older adults: a systematic review. Eur Rev Aging Phys Act. 2021;18(1):24. https://doi.org/10.1186/s11556-021-00278-6. Epub 20211117.

28. Songsorn P, Somnarin K, Jaitan S, Kupradit A. The effect of whole-body high-intensity interval training on heart rate variability in insufficiently active adults. J Exerc Sci Fit. 2022;20(1):48–53. https://doi.org/10.1016/j.jesf.2021.10.003. Epub 20211117.
29. Zhou W, Wan YH, Chen Q, Qiu YR, Luo XM. Effects of Tai Chi exercise on Cancer-Related fatigue in patients with nasopharyngeal carcinoma undergoing chemoradiotherapy: A randomized controlled trial. J Pain Symptom Manage. 2018;55(3):737–44. https://doi.org/10.1016/j.jpainsymman.2017.10.021. Epub 20171106.
30. Hallman DM, Ekman AH, Lyskov E. Changes in physical activity and heart rate variability in chronic neck-shoulder pain: monitoring during work and leisure time. Int Arch Occup Environ Health. 2014;87(7):735–44. https://doi.org/10.1007/s00420-013-0917-2. Epub 20131026.
31. Amekran Y, Damoun N, Taiek N, El Hangouche AJ. Effects of aerobic training on heart rate variability in healthy adults: a systematic review. Gazz Med Italiana Archivio Per Le Scienze Mediche. 2023;182. https://doi.org/10.23736/S0393-3660.23.04952-5
32. Shenoy S, Khandekar Sathe P. A systematic review on the effect of high-intensity training on heart rate variability in sports professionals and healthy young adults. BLDE Univ J Health Sci. 2020;5:114–26. https://doi.org/10.4103/bjhs.bjhs_6_20
33. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 2021;372:n71. https://doi.org/10.1136/bmj.n71
34. The EndNote Team. EndNote. EndNote 21.2 ed. Philadelphia, PA: Clarivate Analytics; 2024.
35. Ouzzani M, Hammady H, Fedorowicz Z, Elmagarmid A. Rayyan—a web and mobile app for systematic reviews. Syst Reviews. 2016;5(1):210. https://doi.org/10.1186/s13643-016-0384-4
36. Slade SC, Dionne CE, Underwood M, et al. Consensus on exercise reporting template (CERT): modified Delphi study. Phys Ther. 2016;96(10):1514–24. https://doi.org/10.2522/ptj.20150668. Epub 20160505.
37. Sterne JAC, Savović J, Page MJ, et al. RoB 2: a revised tool for assessing risk of bias in randomised trials. BMJ. 2019;366:l4898. https://doi.org/10.1136/bmj.l4898. Epub 20190828.
38. Sterne JA, Hernán MA, Reeves BC, et al. ROBINS-I: a tool for assessing risk of bias in non-randomised studies of interventions. BMJ. 2016;355:i4919. https://doi.org/10.1136/bmj.i4919. Epub 20161012.
39. Morris SB, DeShon RP. Combining effect size estimates in meta-analysis with repeated measures and independent-groups designs. Psychol Methods. 2002;7(1):105–25. https://doi.org/10.1037/1082-989x.7.1. PubMed PMID: 11928886.
40. Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. Front Psychol. 2013;4. https://doi.org/10.3389/fpsyg.2013.00863
41. Guyatt GH, Oxman AD, Vist GE, et al. GRADE: an emerging consensus on rating quality of evidence and strength of recommendations. BMJ. 2008;336(7650):924–6. https://doi.org/10.1136/bmj.39489.470347. PubMed PMID: 18436948; PubMed Central PMCID: PMC2335261.
42. Kirmayr M, Quilodrán C, Valente B, Loezar C, Garegnani L, Franco JVA. The GRADE approach, part 1: how to assess the certainty of the evidence. Medwave. 2021;21(2):e8109. https://doi.org/10.5867/medwave.2021.02.8109. Epub 20210317.
43. Guyatt GH, Oxman AD, Kunz R, et al. GRADE guidelines: 7. Rating the quality of evidence–inconsistency. J Clin Epidemiol. 2011;64(12):1294–302. https://doi.org/10.1016/j.jclinepi.2011.03. Epub 20110731.
44. Guyatt GH, Oxman AD, Kunz R, et al. GRADE guidelines: 8. Rating the quality of evidence–indirectness. J Clin Epidemiol. 2011;64(12):1303–10. https://doi.org/10.1016/j.jclinepi.2011.04. Epub 20110730.
45. Guyatt GH, Oxman AD, Kunz R, et al. GRADE guidelines 6. Rating the quality of evidence–imprecision. J Clin Epidemiol. 2011;64(12):1283–93. https://doi.org/10.1016/j.jclinepi.2011.01. Epub 20110811.
46. Guyatt GH, Oxman AD, Montori V, et al. GRADE guidelines: 5. Rating the quality of evidence–publication bias. J Clin Epidemiol. 2011;64(12):1277–82. https://doi.org/10.1016/j.jclinepi.2011.01.011. Epub 20110730.
47. Haddaway NR, Page MJ, Pritchard CC, McGuinness LA. PRISMA2020: an R package and Shiny app for producing PRISMA 2020-compliant flow diagrams, with interactivity for optimised digital transparency and open synthesis. Campbell Syst Reviews. 2022;18(2):e1230. https://doi.org/10.1002/cl2.1230
48. McHugh ML. Interrater reliability: the kappa statistic. Biochem Med (Zagreb). 2012;22(3):276–82. PubMed PMID: 23092060; PubMed Central PMCID: PMC3900052.
49. Villafaina S, Collado-Mateo D, Domínguez-Muñoz FJ, Gusi N, Fuentes-Garcia JP. Effects of exergames on heart rate variability of women with fibromyalgia: A randomized controlled trial. Sci Rep. 2020;10(1):5168. https://doi.org/10.1038/s41598-020-61617-8. Epub 20200320.
50. Wong A, Figueroa A, Sanchez-Gonzalez MA, Son WM, Chernykh O, Park SY. Effectiveness of Tai Chi on cardiac autonomic function and symptomatology in women with fibromyalgia: A randomized controlled trial. J Aging Phys Act. 2018;26(2):214–21. https://doi.org/10.1123/japa.2017-0038. Epub 20180323.
51. Gavi MB, Vassalo DV, Amaral FT, et al. Strengthening exercises improve symptoms and quality of life but do not change autonomic modulation in fibromyalgia: a randomized clinical trial. PLoS ONE. 2014;9(3):e90767. https://doi.org/10.1371/journal.pone.0090767. Epub 20140320.
52. Sañudo B, Carrasco L, de Hoyo M, Figueroa A, Saxton JM. Vagal modulation and symptomatology following a 6-month aerobic exercise program for women with fibromyalgia. Clin Exp Rheumatol. 2015;33(1 Suppl 88):S41–5. Epub 20150317. PubMed PMID: 25786042.
53. Sitges C, Terrasa JL, García-Dopico N, et al. An educational and exercise mobile Phone-Based intervention to elicit electrophysiological changes and to improve psychological functioning in adults with nonspecific chronic low back pain (BackFit App): Nonrandomized Clinical Trial. JMIR Mhealth Uhealth. 2022;10(3):e29171. Epub 20220315. https://doi.org/10.2196/29171. PubMed PMID: 35289758; PubMed Central PMCID: PMC8965676.
54. Figueroa A, Kingsley JD, McMillan V, Panton LB. Resistance exercise training improves heart rate variability in women with fibromyalgia. Clin Physiol Funct Imaging. 2008;28(1):49–54. Epub 20071114. https://doi.org/10.1111/j.1475-097X.2007.00776.x. PubMed PMID: 18005081.
55. Kingsley JD, McMillan V, Figueroa A. The effects of 12 weeks of resistance exercise training on disease severity and autonomic modulation at rest and after acute leg resistance exercise in women with fibromyalgia. Arch Phys Med Rehabil. 2010;91(10):1551–7. https://doi.org/10.1016/j.apmr.2010.07.003
56. Bardal EM, Roeleveld K, Mork PJ. Aerobic and cardiovascular autonomic adaptations to moderate intensity endurance exercise in patients with fibromyalgia. J Rehabil Med. 2015;47(7):639 – 46. https://doi.org/10.2340/16501977-1966. PubMed PMID: 26035415.
57. Zamunér AR, Andrade CP, Forti M, et al. Effects of a hydrotherapy programme on symbolic and complexity dynamics of heart rate variability and aerobic capacity in fibromyalgia patients. Clin Exp Rheumatol. 2015;33(1 Suppl 88):S73–81. Epub 20150318. PubMed PMID: 25786047.
58. Shaffer F, Ginsberg JP. An overview of heart rate variability metrics and norms. Front Public Health. 2017;5:258. Epub 20170928. https://doi.org/10.3389/fpubh.2017.00258. PubMed PMID: 29034226; PubMed Central PMCID: PMC5624990.
59. Billman GE. The LF/HF ratio does not accurately measure cardiac sympatho-vagal balance. Front Physiol. 2013;4–2013. https://doi.org/10.3389/fphys.2013.00026
60. Laborde S, Mosley E, Thayer JF. Front Psychol. 2017;8–2017. https://doi.org/10.3389/fpsyg.2017.00213. Heart Rate Variability and Cardiac Vagal Tone in Psychophysiological Research – Recommendations for Experiment Planning, Data Analysis, and Data Reporting.
61. Wong A, Figueroa A. The effects of low intensity resistance exercise on cardiac autonomic function and muscle strength in obese postmenopausal women. J Aging Phys Act. 2019;27(4):855–60. https://doi.org/10.1123/japa.2018-0418. Epub 20191201.
62. Gisselman AS, D'Amico M, Smoliga JM. Optimizing intersession reliability of heart rate Variability-The effects of artifact correction and breathing type. J Strength Cond Res. 2020;34(11):3199–207. PubMed PMID: 33105371.
63. Cooke WH, Carter JR. Strength training does not affect vagal-cardiac control or cardiovagal baroreflex sensitivity in young healthy subjects. Eur J Appl Physiol. 2005;93(5–6):719 – 25. Epub 20041029. https://doi.org/10.1007/s00421-004-1243-x. PubMed PMID: 15517338.
64. Gerhart H, Tai YL, Fennell C, Mayo X, Kingsley JD. Autonomic modulation in older women: using resistance exercise as a countermeasure. Int J Exerc Sci. 2017;10(2):178–87. Epub 20170301. PubMed PMID: 28344732; PubMed Central PMCID: PMC5360374.
65. Heffernan KS, Fahs CA, Shinsako KK, Jae SY, Fernhall B. Heart rate recovery and heart rate complexity following resistance exercise training and detraining in young men. Am J Physiol Heart Circ Physiol. 2007;293(5):H3180–6. https://doi.org/10.1152/ajpheart.00648.2007. Epub 20070921.

66. Caruso FR, Arena R, Phillips SA, et al. Resistance exercise training improves heart rate variability and muscle performance: a randomized controlled trial in coronary artery disease patients. Eur J Phys Rehabil Med. 2015;51(3):281–9. Epub 20141111. PubMed PMID: 25384514.
67. Selig SE, Carey MF, Menzies DG, et al. Moderate-intensity resistance exercise training in patients with chronic heart failure improves strength, endurance, heart rate variability, and forearm blood flow. J Card Fail. 2004;10(1):21–30. https://doi.org/10.1016/s1071-9164(03)00583-9. PubMed PMID: 14966771.
68. Sentija D, Marsić T, Dizdar D. The effects of strength training on some parameters of aerobic and anaerobic endurance. Coll Antropol. 2009;33:111–6.
69. Quintana DS, Alvares GA, Heathers JA. Guidelines for reporting articles on psychiatry and heart rate variability (GRAPH): recommendations to advance research communication. Transl Psychiatry. 2016;6(5):e803. https://doi.org/10.1038/tp.2016.73. Epub 20160510.
70. Boutcher SH, Park Y, Dunn SL, Boutcher YN. The relationship between cardiac autonomic function and maximal oxygen uptake response to high-intensity intermittent-exercise training. J Sports Sci. 2013;31(9):1024–9. PubMed PMID: 23362808.
71. Carter JB, Banister EW, Blaber AP. The effect of age and gender on heart rate variability after endurance training. Med Sci Sports Exerc. 2003;35(8):1333–40. https://doi.org/10.1249/01.Mss.0000079046.01763.8. f. PubMed PMID: 12900687.
72. Tulppo MP, Hautala AJ, Mäkikallio TH, et al. Effects of aerobic training on heart rate dynamics in sedentary subjects. J Appl Physiol (1985). 2003;95(1):364–72. https://doi.org/10.1152/japplphysiol.00751.2002. Epub 20030321.
73. Alansare A, Alford K, Lee S, Church T, Jung HC. The effects of High-Intensity interval training vs. Moderate-Intensity continuous training on heart rate variability in physically inactive adults. Int J Environ Res Public Health. 2018;15(7). https://doi.org/10.3390/ijerph15071508. Epub 20180717.
74. Buchheit M, Chivot A, Parouty J et al. Monitoring endurance running performance using cardiac parasympathetic function. Eur J Appl Physiol. 2010;108(6):1153-67. Epub 20091222. https://doi.org/10.1007/s00421-009-1317-x. PubMed PMID: 20033207.
75. Gamelin FX, Berthoin S, Sayah H, Libersa C, Bosquet L. Effect of training and detraining on heart rate variability in healthy young men. Int J Sports Med. 2007;28(7):564–70. https://doi.org/10.1055/s-2007-964861. Epub 20070320.
76. Heydari M, Boutcher YN, Boutcher SH. High-intensity intermittent exercise and cardiovascular and autonomic function. Clin Auton Res. 2013;23(1):57–65. https://doi.org/10.1007/s10286-012-0179-1. Epub 20121029.
77. Karavirta L, Costa MD, Goldberger AL, et al. Heart rate dynamics after combined strength and endurance training in middle-aged women: heterogeneity of responses. PLoS ONE. 2013;8(8):e72664. https://doi.org/10.1371/journal.pone.0072664. Epub 20130827.
78. Nuuttila OP, Nikander A, Polomoshnov D, Laukkanen JA, Häkkinen K. Effects of HRV-Guided vs. Predetermined block training on performance, HRV and serum hormones. Int J Sports Med. 2017;38(12):909–20. https://doi.org/10.1055/s-0043-115122. Epub 20170926.
79. Bowman AJ, Clayton RH, Murray A, Reed JW, Subhan MM, Ford GA. Effects of aerobic exercise training and yoga on the baroreflex in healthy elderly persons. Eur J Clin Invest. 1997;27(5):443-9. https://doi.org/10.1046/j.1365-2362.1997.1340681.x. PubMed PMID: 9179553.
80. Cheema BS, Houridis A, Busch L, et al. Effect of an office worksite-based yoga program on heart rate variability: outcomes of a randomized controlled trial. BMC Complement Altern Med. 2013;13:82. https://doi.org/10.1186/1472-6882-13-82. Epub 20130410.
81. Chu IH, Lin YJ, Wu WL, Chang YK, Lin IM. Effects of yoga on heart rate variability and mood in women: A randomized controlled trial. J Altern Complement Med. 2015;21(12):789–95. https://doi.org/10.1089/acm.2015.0138. Epub 20151027.
82. Sinha MK, Maiya GA, Moga AM, Shankar KNS. Exercise dose-response relationship with heart rate variability in individuals with overweight and obesity: protocol for a systematic review and meta-analysis of randomised controlled trials. BMJ Open. 2022;12(4):e047821. https://doi.org/10.1136/bmjopen-2020-047821. Epub 20220425.
83. Pham T, Lau ZJ, Chen SHA, Makowski D. Heart Rate Variability in Psychology: A Review of HRV Indices and an Analysis Tutorial. Sensors (Basel). 2021;21(12). Epub 20210609. https://doi.org/10.3390/s21123998. PubMed PMID: 34207927; PubMed Central PMCID: PMC8230044.
84. Routledge FS, Campbell TS, McFetridge-Durdle JA, Bacon SL. Improvements in heart rate variability with exercise therapy. Can J Cardiol. 2010;26(6):303–12. https://doi.org/10.1016/s0828-282x(10)70395-0. PubMed PMID: 20548976; PubMed Central PMCID: PMC2903986.
85. Henriques T, Ribeiro M, Teixeira A, Castro L, Antunes L, Costa-Santos C. Nonlinear methods most applied to Heart-Rate time series: A review. Entropy. 2020;22(3):309. https://doi.org/10.3390/e22030309. PubMed PMID:.
86. Neves VR, Takahashi AC, do Santos-Hiss MD et al. Linear and nonlinear analysis of heart rate variability in coronary disease. Clin Auton Res. 2012;22(4):175 – 83. Epub 20120403. https://doi.org/10.1007/s10286-012-0160-z. PubMed PMID: 22476435.
87. Sempere-Ruiz N, Sarabia JM, Baladzhaeva S, Moya-Ramón M. Reliability and validity of a non-linear index of heart rate variability to determine intensity thresholds. Front Physiol. 2024;15:1329360. https://doi.org/10.3389/fphys.2024.1329360. Epub 20240205.
88. Burma JS, Graver S, Miutz LN, Macaulay A, Copeland PV, Smirl JD. The validity and reliability of ultra-short-term heart rate variability parameters and the influence of physiological covariates. J Appl Physiol. 2021;130(6):1848–67. https://doi.org/10.1152/japplphysiol.00955.2020. PubMed PMID: 33856258.
89. Plews DJ, Laursen PB, Buchheit M. Day-to-Day Heart-Rate variability recordings in World-Champion rowers: appreciating unique athlete characteristics. Int J Sports Physiol Perform. 2017;12(5):697–703. https://doi.org/10.1123/ijspp.2016-0343. Epub 20161013.
90. Plews DJ, Laursen PB, Stanley J, Kilding AE, Buchheit M. Training adaptation and heart rate variability in elite endurance athletes: opening the door to effective monitoring. Sports Med. 2013;43(9):773–81. https://doi.org/10.1007/s40279-013-0071-8. PubMed PMID: 23852425.
91. Besson C, Baggish AL, Monteventi P, Schmitt L, Stucky F, Gremeaux V. Assessing the clinical reliability of short-term heart rate variability: insights from controlled dual-environment and dual-position measurements. Sci Rep. 2025;15(1):5611. https://doi.org/10.1038/s41598-025-89892-3
92. Rincon Soler A, Silva LE, Fazan R Jr, Murta L. The impact of artifact correction methods of RR series on heart rate variability parameters. Journal of Applied Physiology. 2017;124:jap.00927.2016. https://doi.org/10.1152/japplphysiol.00927.2016
93. Catai AM, Pastre CM, Godoy MF, Silva ED, Takahashi ACM, Vanderlei LCM. Heart rate variability: are you using it properly? Standardisation checklist of procedures. Braz J Phys Ther. 2020;24(2):91–102. https://doi.org/10.1016/j.bjpt.2019.02.006. Epub 20190226.
94. Makivic B, Nikic M, Willis M. Heart rate variability (HRV) as a tool for diagnostic and monitoring performance in sport and physical activities. J Exerc Physiol Online. 2013;16:103–31.
95. Herold F, Gronwald T, Scholkmann F et al. New Directions in Exercise Prescription: Is There a Role for Brain-Derived Parameters Obtained by Functional Near-Infrared Spectroscopy? Brain Sci. 2020;10(6). Epub 20200603. https://doi.org/10.3390/brainsci10060342. PubMed PMID: 32503207; PubMed Central PMCID: PMC7348779.

Publisher's Note