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Monitoring training adaptation: a scoping review of the relationship between self-reported subjective variables and resting vagally-mediated heart rate variability (vmHRV) in adult athletes

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Abstract

Purpose: Explore the relationship between vagally-mediated heart rate variability (vmHRV) and self-reported subjective variables (SVs) in adult athletes, and evaluate the methods used to measure these markers. It aims to provide evidence-based recommendations for athletic monitoring and future research.

Method: Following the PRISMA-ScR framework, a systematic search of Web of Science, PubMed, PsychINFO and Sport Discus identified 9359 records. Additional backward and forward citation searches were conducted. Studies were included if they were peer-reviewed, in English, involved athletes, and examined vmHRV in correlation with SVs. Studies in clinical populations, animals, and reviews were excluded. Thirty-one studies met inclusion criteria. Methodological quality was assessed using the Joanna Briggs Institute (JBI) appraisal, and inter-rater consistency was evaluated with Cohen's Kappa.

Results: SVs were grouped into fatigue-recovery indicators, psychological states, and sleep-related variables. Higher vmHRV often correlated with improved recovery, better sleep, and lower perceived stress, though results were inconsistent. Substantial methodological heterogeneity was also observed. Cohen's Kappa indicated high agreement, and JBI no discrepancies.

Conclusion: The relationship between vmHRV and SVs is complex, influenced by individual (e.g., training status) and methodological (e.g., timing, tools) factors. This review highlights the need for personalised, integrated athlete monitoring, and presents new guidelines for future research.

Keywords: *psychophysiology, sports, fatigue, recovery, perceived stress, overtraining*

Introduction

Athletic performance relies on a carefully managed balance between training and recovery. This balance promotes physiological adaptations through a process called supercompensation (Bompa & Haff, 2009; Kellmann, 2010; Yakovlev, 1967), and mitigates the risks of overtraining and burnout. Overtraining refers to a maladaptive response to excessive training load, resulting in decreased performance, while burnout is a syndrome characterized by emotional and physical exhaustion, reduced sense of accomplishment, and sport devaluation. Both conditions stem from prolonged exposure to chronic stress and share overlapping psychological and physiological manifestations, including vulnerability to injury, illness, and hindered athletic progress and well-being (Kellmann & Kallus, 2001; Moore et al., 2025). However, given that athletes respond to training loads differently, reliable methods to monitor and optimize adaptation are essential for coaches and athletes to support sustained athletic performance (Coutts et al., 2018; Main & Grove, 2009). Despite a variety of tools proposed, there is no single reliable marker to predict and prevent overtraining and burnout (Halson, 2014; Lac & Maso, 2004; Schmitt et al., 2013a). This review aims to explore how psychological and physiological markers of recovery, specifically self-reported subjective variables (SVs) and heart rate variability (HRV), may be associated to better understand how these markers may complement each other in monitoring athlete training status.

SVs have a long-standing role in athletic training as indicators of both recovery and overtraining. SVs capture subjective experiences, based on personal beliefs or feelings (Cambridge University Press, 2024), and often reflect mental stress and fatigue before physiological metrics show changes (Kellmann, 2010; Saw et al., 2016). Among SVs, certain variables (e.g., muscle soreness, perceived tiredness, recovery-stress state) offer insight into the balance needed between training load and recovery (Cheung et al., 2003; Kellmann, 2010; Maso et al., 2005). Other SVs (e.g., mood, anxiety) focus on reporting psychological states, known to impact the health and well-being of athletes, as well as performance (Rice et al., 2016). For instance, anxiety is a psychosocial emotion that influences rehabilitation outcomes (Forsdyke et al., 2016). Sleep-related SVs, such as sleep quality and duration, highlight rest as a critical component of recovery (Vitale et al., 2019), with poor sleep linked to higher injury rates (Gao et al., 2019). Overall, SVs provide insight into athlete adaptation to training. However, several concerns limit their practical use. Research shows that some validated questionnaires have only moderate psychometric properties, and customized tools often used in applied settings may lack reliability and validity (Jeffries et al., 2020; Saw et al., 2017). Athletes can also show poor compliance with daily monitoring, often due to lack of feedback or perceived unfair use of the data, leading to dishonest or inconsistent reporting (Neupert et al., 2019). Furthermore, issues associated with subjective interpretation and external influences can also distort athletes' self-reported status (Heidari et al., 2019). As a result, the use and interpretation of SVs is often approached with caution.

In addition to SVs, physiological measures like HRV, particularly vagally-mediated HRV (vmHRV), have gained prominence as indicators of training adaptation and recovery (Bellenger et al., 2016; Buchheit, 2014; Mosley & Laborde, 2022). HRV refers to the variation in time intervals between successive heartbeats and is considered a non-invasive marker of the autonomic nervous system's regulation of cardiac function (Laborde et al., 2017; Quigley et al., 2024). Specifically, vmHRV reflects parasympathetic nervous system (PNS) activity, which is primarily regulated by the vagus nerve, the tenth cranial nerve and the main afferent pathway of the PNS (Brodal, 2016;

Shaffer et al., 2014). As such, vmHRV provides insight into the body's ability to adapt to both internal and external self-regulatory demands, including those induced by training (Mosley & Laborde, 2022). Among vmHRV parameters, the Root Mean Square of the Successive Differences (RMSSD) and its derivatives (e.g., logarithm of RMSSD) are frequently studied (Laborde et al., 2017; Quigley et al., 2024). Higher resting RMSSD levels have been associated with adaptation to training loads and faster recovery, whereas lower levels are often observed in states of overtraining and fatigue (Bellenger et al., 2016; Buchheit, 2014). Emerging evidence also links lower resting RMSSD to higher levels of burnout, particularly based on several longitudinal studies within the Dresden Burnout Study cohort (Moore et al., 2025; Penz et al., 2018). A recent review further emphasised the value of HRV in determining and monitoring exercise intensity (Tanner et al., 2024). However, individual variability, stemming from age for instance, and contextual factors, such as prior exercise, can affect the magnitude of these associations (Buchheit, 2014; Plews, Laursen, Kilding, et al., 2013). Much like psychological factors, the role of vmHRV as a monitor of training is more nuanced than would be expected (Bellenger et al., 2016; DeBlauw et al., 2023).

To capture a more comprehensive view of athletes' adaptations to training, some studies suggest the potential advantages of monitoring both physiological and psychological dimensions of recovery. Integrating these metrics has shown to reinforce overtraining markers and improve training recommendations (Barrero et al., 2020; Bourdon et al., 2017; Buchheit, 2014; Leti & Bricout, 2013; Plews, Laursen, Kilding, et al., 2013; Rothschild et al., 2024). For example, combining subjective measures like training tolerance with vmHRV data was effective in interpreting changes in post-exercise RMSSD, which isolated RMSSD measures alone struggled to predict (Bellenger et al., 2021). At a theoretical level, this integration also draws from the Neurovisceral Integration Model (NIM), which highlights vmHRV as a measure not only of physical stress responses but also the body's capacity for psychological self-regulation (Thayer et al., 2009). According to the NIM, vmHRV is framed as an indicator of self-regulation capacities that integrate emotional and physiological responses through brain structures based on the central autonomic network (Thayer et al., 2009), with higher vmHRV indicating greater adaptability and emotional regulation (Appelhans & Luecken, 2006; Balzarotti et al., 2017). This integration implies that combining vmHRV and SVs might offer a more holistic perspective on an athlete's adaptability to training (Balzarotti et al., 2017). Nevertheless, a consensus on the integration of these markers is lacking, with ongoing debates about measurement standardization and the best evidence-based and efficient applications for athletic monitoring (Catai et al., 2020; Laborde et al., 2017; Quintana et al., 2016).

The aim of this review is to explore the relationship between RMSSD-based measures of vmHRV and SVs (fatigue-recovery indicators, psychological states, sleep-related measured) in athletic populations. Specifically, it focuses on observational, non-intervention contexts to examine how these variables interact without the influence of experimental manipulation. In addition, it aims to critically evaluate the methods used to measure vmHRV and SVs, with respect to their strengths and weaknesses. By exploring how psychological and physiological markers are interrelated, the review seeks to develop evidence-based recommendations for optimizing athletic monitoring and guiding future research in the field.

Method

This scoping review was developed based on the PRISMA Extension for Scoping Reviews (PRISMA-ScR) recommendations (Tricco et al., 2018). A completed PRISMA-ScR checklist is provided as supplementary material (Supplementary Material A). The protocol was registered on the Open Science Framework (OSF, doi: https://doi.org/10.17605/OSF.IO/VCJHN) prior to study screening. Study selection and methodology quality assessments are also provided on the OSF. A scoping approach was selected due to the substantial heterogeneity in study designs and measurement protocols, which precluded a meta-analysis.

Literature search

Bibliographic searches were conducted on May 15th 2025, in the electronic databases PubMed, PsycINFO, Web of Science Core Collection and SportDiscuss. The terms used for the searches are found in Table 1. Boolean operators (including "AND", "OR" and "NOT") were used. No restriction was applied for publication period, age or sex of participants. The studies found were incorporated into Zotero, and a total of 3,034 duplicate records were manually removed before screening. In addition to database searching, backward citation searching (screening the reference lists of included articles) and forward citation searching (identifying articles that cited the included studies using Google Scholar) were also performed. A total of ten full-text articles could not be accessed, and the ten corresponding authors were contacted to request the texts. Seven authors responded and provided the requested documents, while three did not reply, and those studies were excluded.

Table 1. Terms of search used in Pubmed, PsycINFO, Web of Science and SportDiscuss

Boolean operator	Search terms
	"Heart rate variability" OR "hrv" OR "RMSSD" OR "parasympathetic" OR "vagal" or "vagus"
AND	"Athlet*" OR "sport*" OR "exercise" OR "physical activity" OR "perform*" OR "overload*" OR "taper*" OR "train*" OR "match*" OR "compet*" OR "game*" OR "fitness*"
AND	"Psycholog*" OR "subjectiv*" OR "psychometr*" OR "mood*" OR "questionnair*" OR "wellbeing" OR "well-being" OR "wellness" OR "sleep*"
NOT	"Review" OR "meta-analysis" OR "editorial" OR "protocol" OR "animal" OR "diabetes" OR "cancer" OR "phobia" OR "panic" OR "fibromyalgia" OR "disease" OR "hypertension" OR "overweight" OR "epileps*" or "autis*"

Eligibility criteria

The types of study included were selected based on the following criteria: (a) observational studies (i.e., cross-sectional and cohorts), (b) assess athletes at any competitive level, (c) examined the vmHRV metric RMSSD or its derivatives (e.g., LnRMSSD) in conjunction with SVs, (d) and had undergone peer review to be published within an English language journal or book.

Exclusion criteria included: (e) case reports, psychometric studies focused on developing or validating an instrument, reviews, guidelines, protocols, opinion reports, letters to the editor and non-peer-reviewed works such as doctoral dissertations, (f) animal studies, (g) studies involving populations with clinical illnesses, and (h) a mean sample age below age 18 years.

As additional information, the decision to focus on RMSSD-based vmHRV was based on their methodological robustness and lower susceptibility to respiratory influences compared to other vmHRV indices, such as high-frequency power (Hill & Siebenbrock, 2009; Laborde et al., 2017; Penttilä et al., 2001), along with their widespread use in sports settings (Buchheit, 2014). Also, the definition of *athlete* was based on the work of McKinney et al. (2019), which defines athletes based on the intent of physical activity, the level of competition, and the volume of exercise. The review included individuals engaging in physical activity with the goal of athletic achievement, involving "elite" athletes (>10 h/week of training, highest level of competition), "competitive" athletes (>6 h/week of training, aiming to improve performance), and "recreational" athletes (>4 h/week of training, competing in unregulated events). The remaining population, exercising towards health and fitness, was excluded. Also, *subjective* referred to "influenced by or based on personal beliefs or feelings, rather than based on facts", and *self-reported* refers to "data is information about something provided directly by the person perceiving it" (Cambridge University Press, 2024). No exclusion criteria were applied to subjective self-reported variables.

Study selection

Studies were reviewed by two authors (CA, VH), in a two-step process based on the eligibility criteria: first by screening the title and abstract, and subsequently by reviewing the full text. Agreement with a second reviewer (VH) was analysed using Cohen's Kappa (κ), who reviewed 50 articles for each agreement. Cohen's Kappa was 1.00 for the first screening and 0.85 for full-text selection. A third reviewer (SL) supervised the final inclusion list.

Risk Of Bias (RoB)

The Risk of bias (RoB) of the included studies was evaluated using the critical appraisal checklists developed by the Joanna Briggs Institute (JBI; Moola et al., 2024). Cohort and cross-sectional studies were appraised using the JBI checklists of 11 and 10 questions, respectively. Each item was assessed with responses categorized as *yes, no, unclear* and *not applicable*. Two reviewers (CA, VH), independently conducted the RoB assessments, reporting no discrepancies.

Data extraction

Data extraction was conducted independently by CA and VH, using a standard extraction form developed in Microsoft Excel. Disagreements were discussed and resolved by consensus and, in case of discrepancy, with the participation of a third reviewer (SL). Two discrepancies were identified, both related to the direction of the correlation between vmHRV and SVs, which had to be inferred from figures. One corresponding author was contacted to request missing data. The information extracted included:

a. General: authors, publication year, aim(s) of the study, sample characteristics (size, biological sex, age, sports, geographic origin).
b. vmHRV-related: length of recording, time of the day, periodicity, conditions, position, HRV parameters (all reported parameters were extracted, with specific focus on RMSSD and its derivatives: lnRMSSD, logRMSSD, RMSSDcv [coefficient of variation of lnRMSSD], and 7-day Rolling lnRMSSD), breathing, device used, software and analyses.
c. SV-related: type of variable(s) under study, measurement of the variables, time of the day, periodicity, conditions, device or app, calculations.
d. Reported effects (positive, negative, none): between vmHRV and SVs.

Strategy for data synthesis

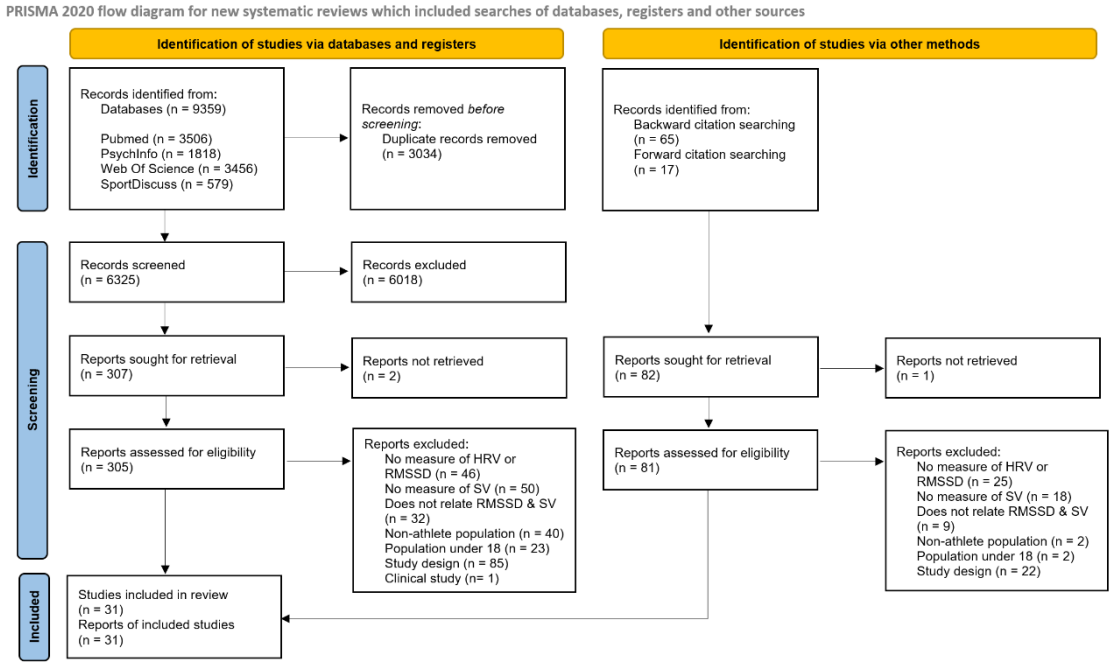
The findings of this review are presented through a narrative synthesis, offering an overview of the existing literature. A narrative synthesis was chosen because the characteristics of the included studies, such as SVs constructs and measurement protocols, were too heterogeneous to support a quantitative summary of effect sizes (McKenzie & Brennan, 2019). Descriptive analyses focus on the correlations between vmHRV and various SVs (fatigue-recovery indicators, psychological states, sleep-related), as well as examine the methodologies employed to evaluate both vmHRV and SVs. Moreover, to assess the consistency of associations between RMSSD-based vmHRV and SVs, including positive, negative, and null findings, the review applied a sum code classification system proposed by Sallis et al. (2000) and used in recent systematic reviews (e.g., Hase et al.2019). This approach focuses on the proportion of studies reporting statistically significant associations. Finally, the synthesis concludes with a discussion addressing the implications of the findings, acknowledges the limitations of current research, and provides evidence-based recommendations to guide future studies in this domain.

Results

Study search and methodological quality

A total of 9359 articles resulted from the initial database search, with an addition 82 coming from forward and backward citation searches. After removing duplicates, and screening based on title and abstract, 386 articles were selected and reviewed at full text. From these, 31 articles finally meet the inclusion criteria and were incorporated into the review. The selection process is summarised in **Fig. 1**.

Fig. 1 PRISMA flow diagram for scientific search and selection of literature (Page et al., 2021)



HRV: Heart Rate Variability; *RMSSD*: Root Mean Square of Successive Differences; *SVs*: Self-reported subjective variables. *Backward citation searching* refers to reference list screening of included articles; *forward citation searching* refers to identifying studies that cited included articles.

All 31 included studies were appraised using the JBI checklists appropriate to their design (cohort or cross-sectional). The methodological quality of the 31 studies was acceptable and all rated as "Include", although 21 studies did not clearly report strategies to address confounding factors. The results of the assessment are provided in Supplementary Material B.

Details on included studies are presented in Supplementary Material C, with an overview of results summarized in Table 2. To address the review's aim of examining the relationship between vmHRV and SVs in athletes and the methodologies used, the results are organized into three sections: 1) vmHRV assessment, 2) SVs assessment, and 3) interrelationships between SVs and vmHRV.

Study characteristics

The included studies were published between 2007 and 2025, with publication rates increasing over time: more articles were published in the last 5 years (2020-2024) than in the previous 13 (2007-2019). Across the 31 studies, sample size ranged from 5 to 117 participants, totalling 514 individuals with a grand-mean age of 23.45 ± 4.17 years. Most studies included females-only (*n* = 12), followed by male-only (n = 8) and mixed-sex cohorts (n = 8). Geographical origins were diverse and are summarized in Table 2. Most participants were classified as elite (n = 20) or competitive (n = 7) athletes, with one study involving recreational athletes. Based on the criteria from McKinney et al. (2019), these classifications indicate participants trained at least 4 hours per week with the intent of athletic achievement. The sports were diverse and categorised as either team-based (e.g., soccer, basketball) or individual-based (e.g., swimming, running).

Table 2. An overview of the scoping review results

Study characteristics	Year of publication		2007 (*n* = 2), 2010 (*n* = 1), 2012 (*n* = 1), 2013 (*n* = 1), 2017 (*n* = 3), 2018 (*n* = 3), 2019 (*n* = 3), 2020 (*n* = 7), 2021 (*n* = 4), 2022 (*n* = 3), 2023 (*n* = 2), 2025 (n = 1)
	Design		Cohort (*n* = 26), Cross-sectional (*n* = 5)
Sample characteristics	Sample size		*n* = 514 Range: 5 – 117.
	Biological sex		Female (*n* = 12), Male (*n* = 8), Mix (*n* = 8), Not reported (*n* = 3)
	Age (mean ± SD)		23.45 ± 4.17
	Geographic origins		USA (*n* = 6), Spain (*n* = 5), France (*n* = 3), Iran (*n* = 2), Japan (*n* = 2), Austria (*n* = 1), Turkey (n = 1), Brazil (*n* = 1), Britain (*n* = 1), Mexico (*n* = 1), Various (*n* = 3), Not reported (*n* = 5)
	Sport studied		**Team-based:** Football (*n* = 8), Volleyball (*n* = 3), Badminton (*n* = 1), Hockey (*n* = 1), Lacrosse (*n* = 2), Rugby (*n* = 1), Waterpolo (*n* = 1) **Individual-based:** Swimming (*n* = 4), Cycling (*n* = 3), Running (*n* = 2), CrossFit (*n* = 1), Dance (*n* = 1), Judo (*n* = 1), Power athletes (*n* = 1), Speed skaters (*n* = 1) **Mix** (*n* = 1)
	Level		Elite (*n* = 20), Competitive (*n* = 7), Recreational (*n* = 1), Not reported (*n* = 3)
vmHRV assessment	Recording protocols	Recording duration	**Orthostatic:** 7-min supine +7-min standing (*n* = 1), 10-min supine + 5-min standing (*n* = 1), 10-min supine + 7-min standing (*n* = 1) **Rest periods:** 1-min rest + 1-min (*n* = 6), 1-min rest + 3-min (*n* = 1), 1-min rest + 5-min (*n* = 2), 5-min rest + 5-min (*n* = 3), 5-min rest + 10-min (*n* = 2), 15-min rest + 8-min (*n* = 1) **Fixed duration:** 1-min (*n* = 4), 5-min (*n* = 1), 10-min (*n* = 5), 15-min (*n* = 1) **During sleep:** 4-hour (*n* = 1), 5-min (*n* = 2)
		Measurement position	Supine (*n* = 15), Seated (*n* = 12), Orthostatic (*n* = 3), Supine & seated (randomized) (*n* = 1)
		Time of the day	Morning, upon waking (*n* = 22), Before competition or training (*n* = 5), During competition (*n* = 1), After competition (*n* = 1), During sleep (*n* = 2), In the lab (*n* = 1), Not specified (*n* = 3)
		Frequency and periodicity	**Once or twice** (*n* = 7), from within 3 days to 6 weeks **Three or four times**: Within 1 week (*n* = 2), Within 2 weeks (*n* = 1), Within 7 weeks (*n* = 1), Within 25 weeks (*n* = 1) **Once per week:** for 13 weeks (*n* = 1), for 14 weeks (*n* = 1) **4-5 times/week**: for 3 weeks (*n* = 3) **Daily:** for 4-14 days (*n* = 5), for 15-30 days (*n* = 7), for 3+ months (*n* = 2)

		Measurement device	**Chest Belt** (*n* = 20): Polar RS800 (*n* = 4), Polar RS800CX (*n* = 2), Polar S810 (*n* = 3), Polar S810i (*n* = 1), Polar V800 (*n* = 2), Polar Team 2 (*n* = 2), Suunto Memory Belt (*n* = 1), Polar Holter system (*n* = 1), EliteHRV with chest strap (*n* = 4) **PPG (Finger-App)**(*n* = 5): HRV4Training with PPG (*n* = 1), ithlete™ with PPG (*n* = 4) **ECG** (*n* = 5): BioHarness (*n* = 1), Finapres Finometer Pro (*n* = 1), FirstBeat Bodyguard 2 (*n* = 1), FirstBeat Sports (*n* = 1), Omega Wave Sport System (*n* = 1) **PPG (Device)** (*n* = 1): Whoop (*n* = 1)
	Standardization & control measures	Inclusion criteria	**Health assessment:** No medical condition or injury (*n* = 7), Medical evaluation (*n* = 4), Anthropometric measures (*n* = 8), Health history questionnaire (*n* = 4), Menstrual cycle (*n* = 4) **Athletic profile:** Experience in the sport (training, competing) (*n* = 5), Current training status (*n* = 5), Consistent team and/or coaching structure (*n* = 7), Vo2Max (*n* = 3), Certain period of the season (*n* = 1) **No specific criteria reported** (*n* = 4)
		Conditions pre/during measurement	**Instructions for breathing frequency**: "Spontaneously" (*n* = 4), Paced 15breaths/min (*n* = 3), "Normally" (*n* = 2), "Naturally" (*n* = 2), Paced 7.5breaths/min (*n* = 1), Paced 10-12breaths/min (*n* = 1), "Stabilize a lowest possible frequency" (*n* = 1), Unclear from article text (*n* = 4), No guidance (*n* = 13) **Experimental room environment** (*n* = 26): Noise (*n* = 13), Light (*n* = 4), Temperature (*n* = 7), People (*n* = 2) **Assessment conditions** (*n* = 23): Speaking (*n* = 11), Moving (*n* = 7), Eyes open (*n* = 1), Elimination (*n* = 4) **Pre-assessment food intake** (*n* = 10): Fasting (*n* = 6), No food for +1h (*n* = 1), No food for +2h (*n* = 1), No food for +3h (*n* = 2) **Pre-assessment substance intake** (*n* = 15): No stimulants for 2-4h (*n* =4), No stimulants for 24h (*n* = 4), No stimulants for 48h (*n* = 1), No stimulants no time specified (*n* = 1), No depressants for 12h (*n* = 1), No depressants or oral contraceptive during the study (*n* = 1), No smoking for +24h (*n* = 1), No smoking for +48h (*n* = 1), No drugs for 1 week (*n* = 1) **Pre-assessment exercise** (*n* = 4): No strenuous exercise for +1h (*n* = 1), no strenuous exercise for 24h (*n* = 3) **Pre-assessment sleep** (*n* = 4): After 6–8h of sleep (*n* = 1), "Normal night of sleep" (*n* = 2), No late sleeping the day before testing (*n* = 1) **Familiarization** with devices and protocol (*n* = 3) **Nothing reported** (*n* = 8)

	HRV parameters and analyses	HRV parameters	**Time domain** (*n* = 76): RMSSD (*n* = 22), LnRMSSD (*n* = 14), logRMSSD (*n* = 2), LnRMSSDcv (*n* = 2), MeanRR (*n* = 3), SDNN (*n* = 10), pNN50 (*n* = 8), RRi (*n* = 6), NN50 (*n* = 2), NN50+ (*n* = 1), NN50– (*n* = 1), pNN50+ (*n* = 1), pNN50– (*n* = 1), SDANN (*n* = 1), SDNNIDX (*n* = 1), STDRR (*n* = 1) **Frequency domain** (*n* = 63): HF (*n* = 13), LF (*n* = 13), HFnu (*n* = 6), LFnu (*n* = 4), FFT (*n* = 3), LogLF (*n* = 1), logHF (*n* = 1), LF/HF (*n* = 14), VLF (*n* = 4), TP (*n* = 3), Ptot (*n* = 1) **Non-linear domain** (*n* = 17): SD1 (*n* = 4), SD2 (*n* = 3), SD1/SD2 (*n* = 1), DFA (detrended fluctuation analysis) (*n* = 2), SampEn (*n* = 2), α1 (*n* = 2), α2 (*n* = 1), DFAa1 (*n* = 1), DFAa2 (*n* = 1) **Other:** Stress Score (*n* = 1), HRV Score (n = 1)
		Software used	Kubios HRV Software (*n* = 14), EliteHRV built-in processing algorithm (*n* = 4), ithleteTM built-in processing algorithm (*n* = 4), Firstbeat Sports proprietary software (n = 1), Custom software (aHRV v11.0.4, Nevrokard Kiauta®, Slovenia) (n = 1), Omega Wave Sport System (Eugene, OR) (*n* = 1), Not reported (*n* = 6)
		Record RHR?	Yes (*n* = 18)
		Correlation analyses between RHR and vmHRV?	No (*n* = 18)
		Rolling averages?	Yes (*n* = 2), No (*n* = 29)
		Coefficient Variation (CV)?	Yes (*n* = 3), No (*n* = 28)
		Smallest worthwhile change (SWC)?	Yes (*n* = 6), No (*n* = 25)
SV assessment	Measurement tool(s)		10-point Likert scale (*n* = 5), 5-Likert scale (*n* = 2), 7-Likert scale (*n* = 3), 8-item questionnaire (*n* = 1), 9-Likert scale (*n* = 3), Athlete Burnout Questionnaire (ABQ) (*n* = 1), Basic sleep questionnaire (*n* = 1), Competitive State Anxiety Inventory-2 (CSAI–2) (*n* = 2), CSAI-2R (*n* = 2), Daily Analysis of Life Demands for Athletes (DALDA) (*n* = 1), Karolinska Sleepiness Scale (KKS) (*n* = 1), Perceived Recovery Status (PRS) (*n* = 2), Profile of Mood States (POMS) (*n* = 2), Perceived Stress Scale (PSS-10) (*n* = 1), Oslo Sports Trauma Research Center (OSTRC) Overuse Injury Questionnaire (*n* = 1), Recovery Stress Questionnaire (RESTQ) (*n* = 1), RESTQ-52 (*n* = 1), RESTQ-Sport (*n* = 3), French Society for Sports Medicine (SFMS) Overtraining questionnaire (*n* = 1), Short Recovery and Stress Scale for Sports (SRS) (*n* = 1), Total Quality of Recovery (TQR) (*n* = 3), Pittsburgh Sleep Quality Index (PSQI) N = 1), Body Awareness Questionnaire (BAQ) (n =1)
	Variable(s) under study*		Anxiety (pre-competitive state, somatic, cognitive, self-confidence) (*n* = 4), Body awareness (n = 1), Burnout (sport devaluation, reduced accomplishment, emotional exhaustion, self-efficacy) (*n* = 1),

	Energy levels (*n* = 1), Fatigue (including “Perceived tiredness”) (*n* = 13), Hours slept (*n* = 1), Mood (*n* = 6), Muscle soreness (DOMS, muscle soreness, general muscle soreness) (*n* = 9), Sleepiness (*n* = 1), Perceived recovery (also includes "Recovery condition" and “Perceived physical fitness”, as well as General recovery, Sport-specific recovery and Total recovery from RESTQ questionnaires) (*n* = 12), Perceived risk of injury (*n* = 1), POMS (Tension, Depression, Anger, Confusion, Vigor, Total Mood Disturbances) (*n* = 2), Total recovery–stress balance (from RESTQ questionnaires) (*n* = 1), Risk of overuse (*n* = 1), Sleep quality (*n* = 10), Stress (also includes General stress, Sport-specific stress, and Total stress from RESTQ questionnaires) (*n* = 14), Stress Tolerance (*n* = 1), Wellbeing (*n* = 7)
Time of the day	Morning, upon waking (*n* = 18), Before competition/training (*n* = 9), During competition (*n* = 1), After competition (n = 1), Not specified (*n* = 5)
Synchronization of measurement between vmHRV and SV	Yes (*n* = 18), No (*n* = 4), Closely (HRV during sleep and SV upon waking) (*n* = 1), On some occasions (*n* = 6), Unclear (*n* = 2)

ECG: Electrocardiogram; *PPG*: Photoplethysmography; *RMSSD*: Root Mean Square of the Successive Differences; *LnRMSSD*: Natural Logarithm of Root Mean Square of the Successive Differences; *logRMSSD*: Logarithm of Root Mean Square of the Successive Differences; *LnRMSSDcv*: Coefficient of Variation of the Natural Logarithm of RMSSD; *MeanRR*: Mean of RR Intervals; *SDNN*: Standard Deviation of NN Intervals*; RRi*: RR Interval; *pNN50*: Percentage of NN Intervals Greater Than 50 ms; *NN50*: Number of NN Intervals Greater Than 50 ms; *NN50*+: Number of Positive NN Intervals Greater Than 50 ms; *NN50*–: Number of Negative NN Intervals Greater Than 50 ms; *pNN50*+: Percentage of Positive NN Intervals Greater Than 50 ms; *pNN50*–: Percentage of Negative NN Intervals Greater Than 50 ms; *SDANN*: Standard Deviation of the Averages of NN Intervals; *SDNNIDX*: Mean of Standard Deviations of NN Intervals in Short Periods; *STDRR*: Standard Deviation of RR Intervals; *HF*: High Frequency Power; *LF*: Low Frequency Power; *HFnu*: High Frequency Power in Normalized Units; *LFnu*: Low Frequency Power in Normalized Units; *FFT*: Fast Fourier Transform; *LogLF*: Logarithm of Low Frequency Power; *logHF*: Logarithm of High Frequency Power; *LF/HF*: Ratio of Low Frequency to High Frequency Power; *VLF*: Very Low Frequency Power; *TP:* Total Power; *Ptot*: Total Power of the Spectrum; *SD1*: Standard Deviation 1; *SD2*: Standard Deviation 2; *SD1*/SD2: Ratio of Short-term to Long-term Variability; *DFA*: Detrended Fluctuation Analysis; *SampEn*: Sample Entropy; *α1*: Short-term Scaling Exponent in DFA; *α2*: Long-term Scaling Exponent in DFA; *DFAα1*: Short-term Scaling Exponent in Detrended Fluctuation Analysis; *DFAα2*: Long-term Scaling Exponent in Detrended Fluctuation Analysis

Muscle soreness: includes articles mentioning DOMS (Delayed Onset Muscle Soreness), Muscle soreness and General muscle soreness; *Fatigue* includes articles mentioning Fatigue, General fatigue, and Muscle fatigue (if ‘Muscle soreness’ was also recorded in the same article); *10-Likert scale* includes 10cm visual analogue scale; *9-Likert scale* includes 9-point Visual analogue scale and 9-point Sliding scale; *Mentions the variables analysed and highlighted in the results of the study.

Methodological insights: vmHRV assessment

Recording Protocols for vmHRV Assessment

As presented in Table 2, the most common positions for recording vmHRV were supine (*n* = 15) or seated (*n* = 12), recorded mostly with 1-min of rest followed by 1-min recording (*n* = 6) or for 10-min (n = 5). Regarding hardware, a variety of ECG and photoplethysmography (PPG)-based devices were used across studies. ECG devices were most common, particularly from the Polar brand paired with a chest strap (e.g., Polar V800, RS800, S810; total n = 14), as well as other devices such as the Suunto Memory Belt (n = 1), OmegaWave Sport System (n = 1), and BioHarness (n = 1). PPG-based systems included the applications ithlete™ (n = 4) and HRV4Training (n = 1), as well as the wrist-worn device Whoop (n = 1). While all these devices measure HRV, they vary in sampling rate, sensor type, and data processing algorithms. A complete list is available in Supplementary Material C.

Most recordings were done in the morning upon waking (*n* = 22), followed by recordings conducted in proximity to training or competition (n = 7), including sessions completed shortly before or after exercise or competitive events. Finally, the duration of the study varied widely, from one recording to daily measured over 3 months.

Standardization and Control Measures in vmHRV Assessment

Standardization procedures and controls for factors influencing vmHRV measurements included factors such as breathing (*n* = 14), experimental room environment (*n* = 26), or intake of food (*n* = 10) or substances (*n* = 15). A total of 8 studies did not report any factor under control. Notably, breathing instructions were diverse, from "Spontaneously" (*n* = 4) to paced 15breaths/min (*n* = 3), paced 7.5breaths/min (*n* = 1), or "Stabilize a lowest possible frequency" (*n* = 1). Table 2 also lists potential confounding factors and participant inclusion criteria, divided into health and athletic factors.

vmHRV analysis and methodological consistency

Regarding the processing of HRV data, key areas include the HRV parameters chosen, the software used, and filters applied. In the included studies, 40 different HRV parameters were analyzed, with some articles investigating multiple parameters. Time domain analyses were the most common type (n = 76), followed by frequency-domain (n = 63) and non-linear domain analyses (n = 17). Kubios in different versions (n = 14) was the most used software, and for details of filters reported see Supplementary Material C. Table 2 also reports methods used to identify trends of HRV.

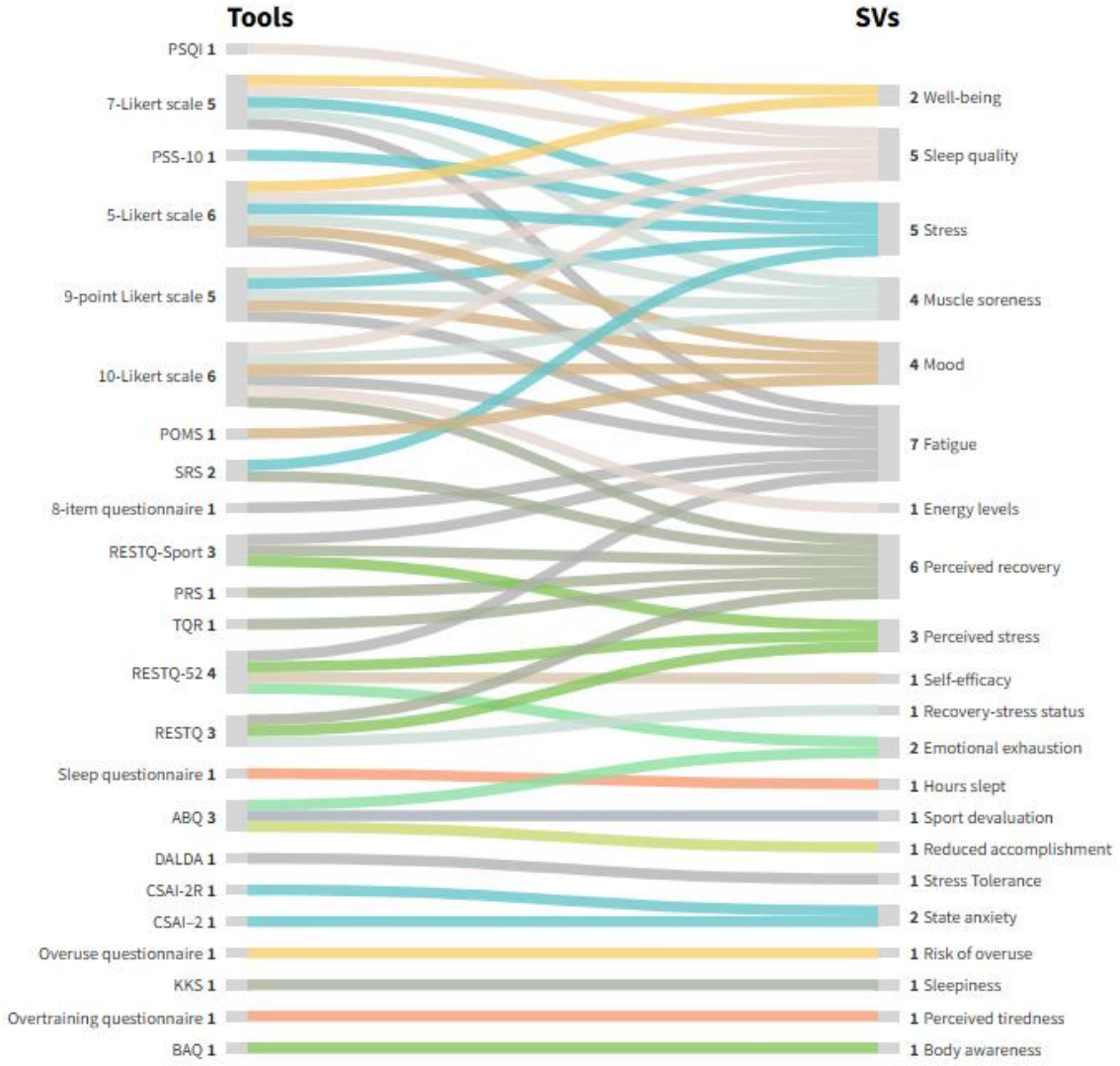
Methodological insights: SV assessment

Assessment and measuring tools

This section presents the SVs reported and measuring tools used in the included studies. In total, over 20 different types of SVs were investigated, which were collected using 19 different types of questionnaires and 4 types of scales. The most popular SVs were fatigue (*n* = 13) and perceived stress (*n* = 14), and the most used questionnaires were the Recovery-Stress Questionnaire for Athletes (RESTQ-Sport) and the Total Quality Recovery Scale (TQR) (*n* = 4 and

3, respectively). Since a same SV was reported from different measuring tools, **Fig. 2** outlines the interrelationship between the SV and the questionnaires and scales utilized to record them.

Fig. 2 Overview of tools (questionnaires and scales) used and the corresponding SV recorded



Like vmHRV, SVs were mostly measured in the morning upon waking (*n* = 18), or in training or competition settings (*n* = 11). Table 2 highlights when vmHRV and SVs were measured in relation to one another. Most measurements were taken simultaneously (*n* = 18), with a study having recorded vmHRV during sleep and SVs upon waking. A total of 6 articles recorded vmHRV and SVs together at least once but not in all instances. "Unclear" means the article did not provide sufficient information to determine timing of vmHRV and SVs measurements (*n* = 2).

SV classification

While all SVs recorded in this review monitored aspects of athletes' states, a suggestion of categorization, based on their primary focus, is provided as follows: first, fatigue and recovery variables encompass perceptions of the capacity to balance training demands with recovery; second, psychological states reflect conditions that may impact athlete health and well-being; and last, sleep-related variables focus on rest as a component of recovery. The categorization of each SVs is presented in Table 3, and definitions are provided in Supplementary Material D.

Table 3. Categorization of SV reported in the reviewed studies

Category	*SV*
Fatigue and Recovery Indicators	Burnout
	Energy levels
	Fatigue
	Muscle soreness or Delayed Onset Muscles Soreness (DOMS)
	Perceived Recovery
	Recovery-stress status
	Risk of overuse
	Stress tolerance
Psychological States	Anxiety
	Body awareness
	Mood
	Perceived stress
	Well-being
Sleep-related Variables	Sleepiness
	Sleep quality

Correlation between SVs and vmHRV

Table 4 presents a summary of the relationships found between vmHRV metrics and SVs in the reviewed studies. The correlations are categorized into positive, negative or none, with significance defined as $p < 0.05$. For instance, perceived recovery was positively associated with vmHRV in nine instances, potentially indicating a relationship between higher vmHRV and improved recovery states in athletes. In contrast, stress and fatigue showed predominantly negative associations, in eight and nine instances, respectively, suggesting that higher values may be associated with lower vmHRV. Other SVs, such as state anxiety and well-being, showed mostly no correlation with vmHRV. Variables like sleep quality, mood or stress have mixed findings, with some studies showing positive or negative correlations and others none. Overall, 93% of SVs present a sum code of zeros or "?", indicating that the correlations are inconsistent or weak. The table also highlights the limited data for certain SVs, like sleepiness, energy levels, or stress tolerance. For complete results, including numerical values, refer to Supplementary Material C.

Table 4. Correlations between vmHRV and SVs, including sum code classifications

SVs		Reference	Correlation between vmHRV and SVs			Sum code		
			Positive	Negative	No association	% Positive	% Negative	Sum Code
Fatigue and Recovery Indicators	**Burnout**	Dobson et al. (2020)			2 lnRMSSD-sup	0	0	**0**
	Energy levels	Flatt et al. (2022)			1 lnRMSSD-seat	0	0	**0**
	Fatigue	Atlaoui et al. (2006), Barrero et al. (2020), DiPasquale et al. (2021), Edmonds et al. (2021), Flatt et al. (2017a), Flatt et al. (2017b), Flatt et al. (2018), Iizuka et al. (2020a), Iizuka et al. (2020b), Parrado et al. (2010), Fields et al. (2020)	1 lnRMSSD-seat 1 RMSSD-stand	2 RMSSD-sup 2 RMSSD-seat 1 lnRMSSDcv-sup 3 lnRMSSD-seat 1 lnRMSSD-ortho	1 RMSSD-sup 1 RMSSD-seat 1 RMSSD-ortho 2 lnRMSSD-seat	12	56	**??**
	Delayed Onset Muscles Soreness (DOMS)	Barrero et al. (2020), Edmonds et al. (2021), Flatt et al. (2017a), Flatt et al. (2017b), Flatt et al. (2018), Flatt et al. (2022)		1 RMSSD-sup 2 lnRMSSD-seat 1 lnRMSSD-ortho	1 RMSSD-stand 1 RMSSD-ortho 1 lnRMSSDcv-sup 3 lnRMSSD-seat	0	40	**??**
	Perceived recovery	Botonis et al. (2022), Flatt et al. (2022), Hauer et al. (2020), Lundstrom et al. (2023), Morales et al. (2019), Miranda-Mendoza et al. (2023), Rundfeldt et al. (2018), Fields et al. (2020), Ravé et al. (2020)	4 RMSSD-sup 1 RMSSD-stand 3 lnRMSSD-sup 1 7-day lnRMSSD-seat		5 RMSSD-sup 3 lnRMSSD-seat	53	0	**??**
	Recovery-stress balance	Lundstrom et al. (2023)			1 RMSSD-sup	0	0	**0**
	Risk of overuse	Williams et al. (2017)		1 7-day lnRMSSD- sup		0	100	**–**
	Stress tolerance	Figueiredo et al. (2019)			1 lnRMSSD-sup	0	0	**0**
Psychological States	**Anxiety**	Mateo et al. (2012), Morales et al. (2013), Oliveira-Silva et al. (2018), Parrado et al. (2010)	1 RMSSD-sup	5 RMSSD-sup	6 RMSSD-seat	8	42	**??**

	Body awareness	Tekin et al. (2025)			1 RMSSD-sup 1 lnRMSSD-sup	0	0	**0**
	Mood	Edmonds et al. (2021), Flatt et al. (2017a), Flatt et al. (2017b), Flatt et al. (2018), Flatt et al. (2022), Nuissier et al. (2007)	2 lnRMSSD-seat	2 lnRMSSD-seat	1 RMSSD-ortho 2 lnRMSSD-seat 1 lnRMSSDcv-sup	25	25	**00**
	Perceived stress	Barrero et al. (2020), Chihaoui Mamlouk et al. (2021), Dobson et al. (2020), Edmonds et al. (2021), Flatt et al. (2017a), Flatt et al. (2017b), Flatt et al. (2018), Hauer et al. (2020), Lundstrom et al. (2023), Miranda-Mendoza et al. (2023), Morales et al. (2019)	1 RMSSD-sup 2 lnRMSSD-sup 1 lnRMSSD-seat	5 RMSSD-sup 1 RMSSD-stand 2 lnRMSSD-seat	2 RMSSD-sup 1 RMSSD-ortho 1 lnRMSSD-sup 3 lnRMSSD-seat 1 lnRMSSD-ortho 1 lnRMSSDcv-sup	19	38	**??**
	Well-being	Flatt et al. (2017b), Juarez Santos-Garcia et al. (2022), Rabbani et al. (2019), Rabbani et al. (2021)	1 lnRMSSD-seat	1 RMSSD-sup 1 lnRMSSDcv-seat	1 RMSSD-sup 3 lnRMSSDcv-sup 2 lnRMSSDcv-seat	11	22	**00**
Sleep-related Variables	**Sleepiness**	Rundfeldt et al. (2018)			1 RMSSD-sup	0	0	**0**
	Sleep quality	Barrero et al. (2020), Edmonds et al. (2021), Flatt et al. (2017a), Flatt et al. (2017b), Flatt et al. (2018), Flatt et al. (2022), Tekin et al. (2025)	3 lnRMSSD-seat 1 7-day lnRMSSD-seat	1 RMSSD-sup 1 lnRMSSD-ortho	1 RMSSD-sup 1 RMSSD-stand 1 RMSSD-ortho 1 lnRMSSD-sup 4 lnRMSSD-seat 1 lnRMSSDcv-sup	27	13	**00**

Percentages round to the nearest whole number and may not total 100%. The "Sum Code" classification is adapted from Sallis et al. (2000) and reflects the proportion of studies reporting a statistically significant association. Sum codes indicate: "+" ≥60% of studies reported a positive association, "–" ≥60% of studies reported a negative association, "0" ≤33% of studies found no correlation in either direction, "?" reflects inconsistent findings, with 34–59% of studies showing a positive or negative association. Codes are doubled (e.g., "++", "--", "00", "??") when the number of studies contributing to the classification is four or more. The indexed abbreviations refer to the vmHRV metric and the body position during recording, including RMSSD (Root Mean Square of the Successive Differences), lnRMSSD (Natural Logarithm of RMSSD), lnRMSSDcv (Coefficient of Variation of lnRMSSD), and 7-day lnRMSSD (7-day rolling average lnRMSSD), *sup:* supine; *seat:* seated; *stand:* standing; *ortho:* orthostatic.

Discussion

This scoping review aimed to investigate the relationship between vmHRV and SVs in athletic populations, as well as the methodologies used for the recording of these metrics. A systematic analysis of 31 observational studies revealed considerable variability in both the reported correlations and methodology, underscoring the complexity of integrating vmHRV and SVs in athletic monitoring. This section discusses the findings by situating them within the broader theoretical and empirical context, and finally addresses the challenges, proposing recommendations for future research.

The studies reviewed involved athletes with a mean age of 23.5 ± 4.2 years, reflecting a young adult population, and most (20 out of 31 studies) were classified as elite-level athletes based on the criteria proposed by McKinney et al. (2019). These individuals engage in more than 10 hours of training per week and participated in structured competition, representing high-performance environments where precise monitoring tools are critical. By encompassing both individual sports (e.g., speed skating) and team sports (e.g., football), the sample provided diverse contexts, providing an understanding of how vmHRV and SVs interact across different athletic settings. This diversity reinforces the relevance of exploring these markers in varied sports contexts.

Relationship between vmHRV and SVs: correlation results

The correlation found between vmHRV and SVs are presented following the suggested categories of SVs from Table 3.

Fatigue and recovery indicators

The first group of SVs reflects an athlete's capacity to balance training demands with recovery. This category is grounded in the Scissor's Model (Kellmann & Kallus, 2001), which conceptualizes stress and recovery as interrelated processes. According to the model, stressors, whether physical or psychological, impact performance and adaptation, while recovery is a multilevel process involving psychological, physiological, and social factors that restore baseline conditions. Importantly, when perceived stress levels do not exceed physical and mental recovery capacities, athletic performance improves (Heidari et al., 2019; Kellmann, 2010). Thus, monitoring recovery is critical, as insufficient levels may lead to overtraining, burnout, and injury (Gerber et al., 2023; Smith, 2003).

In this review, the two most used tools to measure perceived stress and recovery were the TQR (Kenttä & Hassmén, 1998), and the RESTQ- questionnaires (Kellmann & Kallus, 2024). The findings indicate that perceived recovery was positively correlated with vmHRV in 53% of cases, while fatigue and muscle soreness were negatively correlated in 56% and 40% of cases, respectively. These findings align with existing literature suggesting that higher vmHRV reflects greater parasympathetic activity and increased parasympathetic influence on the heart, which is associated with improved recovery states (Buchheit, 2014; Quigley et al., 2024), whereas increased physical strain correlates with reduced vmHRV, reflecting the body's reduced recovery capacity under physical stress (Mosley & Laborde, 2022; Plews, Laursen, Stanley, et al., 2013). For example, Flatt & Howells (2022) found that fitness level and perceived fatigue significantly predicted variations in LnRMSSDcv. Overall, these findings reinforce current knowledge about

the recovery-stress balance and its relationship with vmHRV, and also support the NIM, which posits that vmHRV reflects the central autonomic network's ability to regulate both emotional and physical stress responses (Thayer & Lane, 2000). Thus, the positive correlations between vmHRV and recovery-related variables, and the negative correlations with fatigue indicators, highlight vmHRV's role as a potential biomarker of both physiological and psychological readiness.

The sum code classifications in Table 4, however, suggest that these relationships are not consistent across studies and instead point to a more nuanced relationship than initially thought. Despite promising directional trends, fatigue, perceived recovery and DOMS were overall classified as "??", indicating inconclusive findings even if studied in multiple articles. Similarly, burnout which has previously been associated with reduced vmHRV, specifically lower RMSSD (Wekenborg et al., 2019), was assigned a "0", reflecting an lack of significant associations. Interestingly, diverging results were sometimes observed within the same study. For instance, Edmonds et al. (2021) found positive correlations between fatigue and vmHRV in certain athlete subgroups (e.g., sophomores), but not in others (e.g., freshmen, seniors). Similarly, Rundfeldt et al. (2018) observed that RMSSD and perception of recovery positively correlated in the "non-finisher" group of an ultra-endurance race, but not in "finisher". Thereby, inconsistencies might stem from study-specific conditions and context-specific factors that influence outcomes, indicating that subjective perceptions of recovery do not always align with physiological measures. This idea is supported by the finding that vmHRV is often reduced before competition indicating readiness to perform, rather than fatigue that could impair performance (Buchheit, 2014). Findings in neuroscience also show that subjective perceptions of fatigue often diverge from physiological markers of fatigue (Casamento-Moran et al., 2023). In addition, external factors such as consecutive matches can influence recovery perceptions (Botonis et al., 2022).

In short, while vmHRV is generally considered to correlate negatively with fatigue, tiredness, and burnout, and positively with recovery, the inconsistent or weak findings across studies highlight a potential complex interplay. This suggests a need for context-sensitive interpretations in assessing athlete fatigue and recovery states (Saw et al., 2016). Integrating objective indices of autonomic regulation, such as vmHRV, with subjective experiences of fatigue and recovery, though SV, may offer researchers and practitioners a more holistic and individualised understanding of an athlete's readiness to train and compete.

Psychological states

This second group of variables explores athletes' psychological states, particularly those related to affect regulation, perceived stress, and anxiety, with the NIM providing a theoretical foundation for grouping these SVs together. The NIM posits that the prefrontal cortex regulates the body's response to physical or perceived stress through cardiac vagal activity, reflected in vmHRV (Thayer & Lane, 2000). Athletes with high psychophysiological flexibility (i.e., higher neurovisceral integration, and higher vmHRV) tend to exhibit superior self-regulatory capacity and emotional resilience (Gross & Thompson, 2007; Park & Thayer, 2014). Conversely, lower vmHRV is associated with higher anxiety and impaired emotion regulation (Gaebler et al., 2013; Pittig et al., 2013). Despite these theoretical expectations, the findings in this review were inconsistent. For instance, mood had less than one-third of studies with a significant association in either a positive or negative direction, while anxiety and perceived stress presented

inconclusive results. For stress specifically, 38% of results reported negative correlations with vmHRV (Barrero et al., 2020; Chihaoui Mamlouk et al., 2021; Flatt et al., 2018; Lundstrom et al., 2023; Morales et al., 2019), while 42% showed no association at all. This near-even split highlights the complexity of stress as a construct and the challenge of drawing conclusions from the current evidence.

The inconsistencies may be, in part, explained by how psychological variables are subjectively experienced and contextually interpreted. For instance, in the case of stress, the Transactional Model of Stress and Coping (Lazarus & Folkman, 1984) posits that stress is not just a physiological response but a product of how individuals appraise and cope with situations. In this framework, stress perceived as a challenge may elevate vmHRV, while stress perceived as overwhelming can have the opposite effect (Meijen et al., 2020). This dual interpretation could explain the mixed findings across the reviewed studies. Furthermore, as noted by Mosley and Laborde (2022), stress is physiologically multifaceted, involving a complex interplay between the HPA-axis and the ANS, which vmHRV alone cannot fully capture. Taken together, perceived stress appears as a complex variable to assess, and this complexity may extend to other psychological variables, where variability in results is also evident. For example, well-being showed contradictory findings, even within the same research team. For instance, Rabbani et al. (2019) initially linked higher LnRMSSD to improved well-being (lower Hooper's index), but later reported a negative correlation (Rabbani et al., 2021). Overall, the findings also reinforce the importance of context when interpreting psychological variables in relation to vmHRV.Methodological differences further complicate the relationship between vmHRV and psychological states. For example, the calculation of well-being scores varied across studies, with some using summed or averaged scores of a mix of variables like fatigue or sleep quality, while others analysed variables individually or used different scales (Supplementary Material C). This lack of standardization complicates cross-study comparisons and underscores the need for consensus on protocols. As another example, Juarez Santos-Garcia et al. (2022) reported differing correlations between well-being and RMSSD depending on whether measurements were based on 5 minute or 4 hour recordings during sleep. Temporal factors are also important: subjective well-being (Grainger et al., 2022), fatigue and muscle soreness (Fazackerley et al., 2019) recover slower than ANS responses, potentially leading to lack of correlation in same-day assessments. Such disparities raise concern and highlight the importance of standardizing protocols for both vmHRV and SVs.

In summary, the heterogeneity in observed associations between vmHRV and psychological states reflects an interplay of individual variability, methodological inconsistencies, and the dynamic nature of these metrics. While the NIM provides a theoretical basis for linking vmHRV to affective regulation, the empirical evidence remains mixed, and the findings reinforce the need for standardized measurement protocols and context-aware interpretations.

Sleep-related

This category includes SVs related to sleep, which is critical for athlete recovery, performance, and long-term health (Vitale et al., 2019). In the present review, findings on the association between vmHRV and subjective sleep quality were mixed. Only 27% of results indicated a positive correlations between vmHRV and sleep quality, suggesting that better sleep might enhance vmHRV (Chouchou & Desseilles, 2014; Lins-Filho et al., 2023; Sajjadieh et al., 2020;

Schlagintweit et al., 2023). These findings support the hypothesis that sleep facilitates physical restoration, particularly after physical effort (Chandrasekaran et al., 2020; Shapiro et al., 1981). This is supported by evidence linking improvements in vmHRV with improvements in subjective sleep qualityfollowing a 30-day slow-paced breathing intervention (Laborde et al., 2019). However, 60% of reviewed studies reported no significant correlation, suggesting that although there is evidence linking better perceived sleep with increased vmHRV, the overall body of research in athletes remains inconclusive. From a theoretical standpoint, this variability is not entirely surprising. The NIM (Thayer et al., 2009) posits that vmHRV reflects the adaptability of the central autonomic network in regulating recovery processes, including sleep. When sleep is perceived as restorative, it may coincide with higher cardiac vagal activity, reflected in increased vmHRV. In this sense, positive correlations could indicate enhanced parasympathetic modulation and recovery capacity. However, the high rate of non-significant findings also suggests that vmHRV and perceived sleep quality do not always align.

One explanation is the lies in the distinction between subjective and objective sleep quality. In subjective assessments, the influence of stress, emotional dysregulation, or perception biases, can simultaneously distort the evaluations of sleep (Harvey & Tang, 2012; Tworoger et al., 2005). In fact, there are known differences between perceived and actual sleep quality well documented in both healthy individuals and in clinical samples, such as insomnia patients (Harvey & Tang, 2012). For instance, Goelema et al. (2019) found that men tended to overlook nighttime awakenings compared to women, leading to a more positive self-assessment of sleep quality. Additionally, other factors such as mental or physical stress can further impair the perception of sleep quality (Tworoger et al., 2005), further complicating subjective assessments. Thus, while research confirms that acute sleep deprivation impairs athletic performance (Gong et al., 2024), and that vmHRV correlates with objective sleep parameters (Fonseca et al., 2020), its relationship to subjective sleep quality assessments is still unclear. This review's findings suggest that vmHRV might better reflect physiological processes than subjective perceptions of sleep.

Given the importance of sleep in athlete health and performance (Doherty et al., 2021), it is essential that future research addresses these measurement limitations. To effectively integrate sleep-related SVs with vmHRV, researchers should prioritize longitudinal data collection to capture variability across multiple nights, use validated assessment tools, and account for individual differences in sleep perception, stress reactivity, and recovery behaviour (Goelema et al., 2019). A combined approach that includes both objective (e.g., vmHRV) and subjective measures could improve the utility of sleep-related SVs in monitoring athlete recovery and performance.

Methodological Issues and Recommendations

Discrepancies in the correlations between vmHRV and SVs might stem from methodological inconsistencies. For instance, Table 4 aimed to illustrate how many different RMSSD-based vmHRV parameters and recording positions (e.g., seated, supine, orthostatic) were used within the same SV category. This variability can introduce bias when interpreting results, as different parameters and postures may reflect distinct aspects of autonomic regulation. Thus, despite the widespread use of vmHRV and SVs in assessing training adaptation in athletes (Olmos et al., 2024), the review identified substantial differences in measurement protocols that complicated

cross-study comparison (Laborde et al., 2017). Similar challenges have been reported in elite soccer research (Mirto et al., 2024) and aligns with calls for standardization in exercise-based HRV research, where promising HRV thresholds face validation challenges due to inconsistent methodologies hindering comparability (Kaufmann et al., 2023). This section outlines methodological practices, limitations, and recommendations for standardization.

vmHRV Assessment: Standardization

- **Inclusion criteria:** Control over participant health status varied, with only 7 of 31 studies excluding participants with medical conditions, despite their known impact on autonomic regulation (Malik et al., 1996). For participants with medical conditions, documentation of medications and conditions is essential (Laborde et al., 2017). Also menstrual cycle considerations were reported in only 4 studies, despite its influence on RMSSD (Kokts-Porietis et al., 2020; Sherman et al., 2022). Ideally, participants would be tested in a given phase (e.g., follicular phase in Morales et al., 2013). Athletic experience, coaching structure, and seasonality also relate to vmHRV, yet were inconsistently reported. For example, vmHRV and SVs can vary depending on the time of the season, but only 5 studies accounted for this by measuring vmHRV outside of competition periods (e.g., Chihaoui Mamlouk et al., 2021). Also, more experienced athletes usually exhibit higher vmHRV (Aubert et al., 2003; Kozjek et al., 2016), and similar team or coaching structures can improve comparability by reducing variability in study outcomes (Proietti et al., 2017). Therefore, future research is encouraged to provide detailed reporting on participants' health and training-related variables.
- **Conditions pre/during measurement:** Studies varied in controlling external, physiological, and behavioural factors that affect vmHRV. One-third failed to regulate environmental variables like temperature and lighting, which affect autonomic function (Achten & Jeukendrup, 2003; Laborde et al., 2017; Pitzalis, 1996). Similarly, pre-assessment consumption of caffeine, alcohol, or food was inconsistently managed, despite their known effects on vmHRV (Lu et al., 1999; Quintana et al., 2013; Zimmermann-Viehoff et al., 2016). The recommendation is to avoid caffeine for two hours and alcohol for 24 hours before testing (Laborde et al., 2017). Breathing control also varied, with 14 studies providing specific guidance ranging from spontaneous to paced, and 16 studies offering unclear or no guidance. Although RMSSD is less influenced by breathing rate than other parameters (Hill & Siebenbrock, 2009), spontaneous breathing is recommended to avoid artificially elevated vmHRV values (Laborde et al., 2017). Given the portential effects of these factors, controlling and reporting them is important to maintain a high level of standarization.

vmHRV Assessment: Recording Protocols

- **Recording duration:** Most studies followed Task Force guidelines (Malik et al., 1996), using recordings of 1 (n = 10) or 5 minutes (n = 7) recordings. Interestingly, while short-term (5 min) and ultra-short-term (1 min or less) recordings share mathematical formulas, they capture different physiological processes and are not fully interchangeable (Shaffer et al., 2020). However, under resting conditions, RMSSD for ultra-short term recordings has proven reliable in both athletes and non-athletes (Esco & Flatt, 2014; Munoz et al., 2015), supporting their practical use due to time efficiency. Regarding prestabilization, a 1 to 15 minute rest period prior to recording was employed in 15 studies, providing stabilization of

vmHRV indices and enhancing reliability (Krejčí et al., 2018). Nonetheless, research on this aspect remains limited (Mirto et al., 2024).

- **Measurement position:** Supine (n = 15) and seated (n = 12) positions were almost equally represented, with supine yielding higher vmHRV values due to minimized sympathetic activation (Gronwald et al., 2024). However, orthostatic measurements, which capture dynamic physical stress responses, were underrepresented despite their potential for assessing recovery and exertion (Bourdillon et al., 2017; Gronwald et al., 2024; Schmitt et al., 2015). In fact, recent research has highlighted the advantages of orthostatic testing as a means to assess autonomic reactivity and fatigue levels, particularly in mitigating PNS saturation in well-trained endurance athletes (Gronwald et al., 2024). The Vagal Tank Theory aligns with this perspective, proposing that phasic vmHRV, reflecting responses to short-term stressors, provides more information when reactivity to a stimulus is measured, compared to assessments conducted solely in a resting position (Laborde et al., 2018). In Rabanni et al. (2021), seated LnRMSSD showed stronger associations with training status than supine.
- **Time of the day:** Morning assessments were most common, recorded in 22 studies, offering stable baselines unaffected by daily activities (Buchheit, 2014). Fewer studies (n = 7) measured vmHRV near training or competition, which can provide insights into acute stress responses (Buchheit et al., 2007; Stanley et al., 2013) but may introduce variability due to immediate physical exertion (Laborde et al., 2018). Finally, vmHRV during sleep was only measured in 2 studies, despite its potential for autonomic assessment without external interference (Brandenberger et al., 2005) and more tools available (Bianchi & Mendez, 2013). Thus, while there is still no clear consensus on the optimal time for HRV monitoring, particularly between morning and nocturnal assessments, morning measurements offer greater standardization, and provide a replicable approach (Plews, Laursen, Stanley, et al., 2013).
- **Measurement device:** ECGs remain the gold standard for vmHRV measurement (Berntson & Stowell, 1998; Laborde et al., 2017; Quigley et al., 2024), but chest belts, used in 20 studies (e.g., Polar RS800), dominated in capturing electrocardiac signals in the present studies. Although not classified as ECGs, chest belts provide accurate RR interval data (Gilgen-Ammann et al., 2019; Pasadyn et al., 2019). PPG devices were used in 6 studies, and while less precise (Singstad et al., 2021), offer accessible, field-based alternatives (Holmes et al., 2020; Plews et al., 2017). In this way, both chest belts and PPG-based devices help bridge the gap between laboratory science and field-based vmHRV monitoring, but while they can be valuable in practical settings, researchers should acknowledge their limitations in the articles.

vmHRV Assessment: analysis and methodological consistency

- **HRV parameters:** A total of 40 different parameters of HRV were reported, with the vagally-mediated RMSSD parameter as the most common (n = 22) due to its reliability and ease of calculation (Buchheit, 2014; Mirto et al., 2024). Some studies favoured its logarithmic transformation (LnRMSSD), as it stabilizes data and reduces sensitivity to outliers (Penttilä et al., 2001; Plews, Laursen, Stanley, et al., 2013).
- **Software and data processing:** Most analyses used Kubios software, known for its user-friendly interface and robust filtering options (Tarvainen et al., 2014). However, filters were

inconsistently reported, compromising replicability (Berntson & Stowell, 1998; Shaffer & Combatalade, 2013). Proper reporting of data processing is critical (Laborde et al., 2017).

- **Additional analyses:** When monitoring long-term changes, analyses like rolling averages, coefficients of variation (CV), and smallest worthwhile change (SWC) can help reveal trends in vmHRV data. CV quantifies day-to-day variability, offering insights into physiological adaptation, while SWC identifies practically meaningful changes (Buchheit, 2014; Plews, Laursen, Stanley, et al., 2013). Also, despite 18 studies measuring resting heart rate alongside vmHRV, none correlated them, an omission worth exploring (Plews et al., 2012; Sacha, 2014). Although not all longitudinal studies implemented these calculations, the findings indicate a shift towards the common use of these methods.

Self-reported subjective variables

The analysis of SVs across studies revealed significant heterogeneity in both the variables measured and the tools used. As illustrated in Fig. 2, over 20 SVs were assessed using 19 questionnaires and 4 types of scales. Perceived stress and fatigue, for example, were evaluated using diverse tools, from the Perceived Stress Scale-10 (PSS-10) to Likert scales. Researchers also varied in their reporting terminology: for instance, seven studies measured multiple single-item variables such as perceived fatigue and sleep quality and aggregated them into composite scores, but two of these studies referred to the score as the Hooper Index (Rabbani et al., 2019; Rabbani et al., 2021), while five labelled it as well-being (e.g., Flatt et al., 2017). Moreover, another four studies reported the same single-item measures individually, without aggregation (e.g., Chihaoui Mamlouk et al., 2021). At the same time, many SVs were poorly defined; for example, *stress* was often ambiguous, lacking justification as a stressor, distress, or general stress (Wheaton & Montazer, 2009). Improving the clarity and definition of these variables is key to reduce bias. Regarding tools, the most common were the RESTQ-Sport and TQR, with recognized reliability and validity (Kellmann & Kallus, 2024; Kenttä & Hassmén, 1998). Likert scales were also widely used but varied in format (e.g., 5, 7, 10 points). Thus, despite the use of SVs in assessing training adaptation, the lack of standardization limits cross-study comparisons. In the future, validated, sport-specific tools should be prioritized while considering the pros and cons of each one (DeVellis, 2016; Jebb et al., 2021).

Study duration

The duration of the reviewed studies ranged from single measurements (n = 7) to daily recordings over three months (n = 2), raising questions about optimal monitoring frequency. Given the non-linear nature of HRV responses to life stressors (Plews et al., 2017), single-day (Bechke et al., 2020) and long-term (Nakamura et al., 2015) monitoring provides more accurate insights into HRV responses to stress and recovery, especially for establishing individual baselines in athletes and detect meaningful changes (Plews, Laursen, Stanley, et al., 2013). Nonetheless, daily long-term monitoring may not always be practical, as it may cause participant fatigue or inaccurate responses. A hybrid approach, combining brief daily assessments with periodic comprehensive tools, balances accuracy with practicality. For instance, daily self-reports could be complemented by weekly POMS or RESTQ-Sport questionnaires (Saw et al., 2015). Moreover, the frequency of HRV monitoring would depend on the analysis expected: weekly averages work well for microcycle trends (Nakamura et al., 2015), while daily measures are necessary to monitor CVs.

Simultaneous measurement of vmHRV and SVs

Simultaneous measurement of vmHRV and SVs is key for understanding their interaction. In this review, 58% of studies measured both variables concurrently (e.g., in the morning), capturing real-time links between vmHRV activity and subjective states. This approach aligns with the NIM (Thayer & Lane, 2000), which emphasizes the dynamics between physiological regulation and emotional responses. In contrast, measuring vmHRV and SVs at different times of the day (e.g., Miranda-Mendoza et al., 2023) or on different days (e.g., Williams et al., 2017), risks missing phasic fluctuations and stress-recovery correlations. For instance, Mohammadi et al. (2019) found that subjective stress and physiological markers like cortisol did not align when measured separately. Overall, while some recommend staggered measurement frequencies (Saw et al., 2015), this review argues that simultaneous assessment provides clearer insights into the stress-recovery balance.

Methodological guidelines

The array of tools and protocols observed in the studies underscores the need for reliable and standardized methodologies in vmHRV and SVs research. While existing guidelines offer general directions for HRV measurement (Catai et al., 2020; Laborde et al., 2017; Quigley et al., 2024; Quintana et al., 2016) and reporting consistency (Bossuyt et al., 2003; Dobbs et al., 2019; Quigley et al., 2024), the field of sports science requires more specific, actionable protocols. Based on the findings discussed, a methodological checklist is proposed for conducting and reporting vmHRV and SVs research in athletes. Presented as a table for practical use as suggested previously (Han et al., 2017), it can be adapted to suit the specific requirements of each study. References and detailed recommendations are provided throughout the manuscript or referenced in Table 5.

Table 4. Methodological checklist for vmHRV and SV research in athletes

	Methodological Information
☐	Aim(s) of the study
☐	Study design
	Sample
☐	Allocation (Lalanza et al., 2023)
☐	Sample size: with justification (e.g., based on power analysis)
☐	Inclusion/exclusion criteria. E.g.: Athletic profile (e.g., experience in the sport, season/training status, team and/or coaching structure)
☐	Medication or health factors (e.g., antidepressants, antihypertensives, medical condition or injury, menstrual cycle)
	Demographic Characteristics
☐	Anthropometric measures (e.g., weight, height) (Yi et al., 2013)
☐	Biological sex assigned at birth (Umetani et al., 1998)
☐	Gender identity (male, female, non-binary, other)
☐	Age (e.g., mean and/or range) (Umetani et al., 1998)
☐	Geographical origin (e.g., region or country distribution)
☐	Sport: specific sports or activity type
☐	Level (e.g., recreational, competitive, elite)
	vmHRV Protocol and Analysis

☐	Recording duration: length of recording, including rest periods (if applicable)
☐	Measurement position: participant position during recording (e.g., supine, seated)
☐	Time of the day: timing of HRV measurement (e.g., morning upon waking, pre/post-exercise)
☐	Measurement device: provide details on the device used (e.g., ECG, PPG) and specifications
☐	HRV parameters: identify the HRV metrics analysed (e.g., RMSSD, LnRMSSD)
☐	Software and data processing: specify the software used and any applied filters
☐	Frequency and periodicity: describe the number and timing of repeated measurements (e.g., daily, weekly)
☐	Additional analyses: mention complementary analyses performed (e.g., LnRMSSD/R-R ratio, rolling averages, CV, SWC)
	Conditions Pre/During Measurement
☐	Breathing instructions: specify the type of breathing used, if applicable (e.g., spontaneous, paced at specific rates)
☐	Environmental room conditions: control and report room settings (e.g., temperature, lighting, noise levels)
☐	Substance intake: detail restrictions on pre-assessment intake (e.g., caffeine, alcohol, smoking, energy drinks)
☐	Food intake: detail protocols on fasting or meal timing before assessment (e.g., no intake for 2h)
☐	Exercise restrictions: detail protocols for pre-assessment exercise (e.g., avoiding for 24h) (Stanley et al., 2013)
☐	Sleep requirements: detail sleep guidelines (e.g., minimum hours) (Stein & Pu, 2012)
☐	Participant familiarization: detail whether participants are trained on devices and procedures (Robertson et al., 2014)
	Subjective Self-Reported Variables Protocol
☐	Measurement tools: specify the questionnaire or scale used, including validation status and reliability (if available).
☐	Variable under study: indicate the subjective variable. Ideally, categorize the variable under fatigue-recovery indicators, psychological states, sleep-related factors, or other domains.
☐	Frequency and periodicity: describe the number and timing of repeated measurements (e.g., daily, weekly)
☐	Synchronization with vmHRV: clearly specify whether vmHRV and SV are recorded simultaneously or at different times

Implications for athletic monitoring

This scoping review is a response to the increasing demand for effective tools and protocols to monitor athletes' training adaptation, by exploring the integration of vmHRV and SVs metrics. The findings support their complementary application for three reasons.

First, the review highlights that vmHRV and SVs metrics often do not align, as suggested by prior research (Saw et al., 2016; Vacher et al., 2019). This variability reflects the multifactorial nature of these measures, where factors like stress perception influence both vmHRV and SVs outcomes, making it difficult to expect linear relationships. While it might seem ideal for low vmHRV to consistently correlate with high fatigue, for example, findings indicate the relationship is not straightforward. By providing distinct yet complementary information, adopting an approach with both vmHRV and SVs provides a more comprehensive view of training adaptation.

Second, the results highlight the role of context and associated limitations of relying on a single marker to monitor adaptation. Different SVs categories (fatigue-recovery indicators, psychological states, and sleep-related) offer unique insights shaped by individual and situational factors (e.g., training phase, pre-competition anxiety or travel-induced sleep disruptions) (Ayuso-Moreno et al., 2020; Da et al., 2015). For example, increased training load typically decreases vmHRV and fatigue-recovery indicators, but the absence of negative SVs feedback despite physiological declines might indicate positive adaptation (Coutts et al., 2018). Incorporating and refining the interpretation of physiological data could further contextualize changes and refine our understanding of athlete health and performance. This would include, for example, orthostatic HRV assessment to inform about autonomic reactivity beyond resting HRV alove (Gronwald et al., 2024), or other biomarkers such as cortisol, a glucocorticoid hormone involved in metabolic processes such as protein breakdown, increased gluconeogenesis, and immune function. In sport contexts, acute increases of cortisol are observed following moderate to high-intensity exercise (Hill et al., 2008) and are often used to assess training strain and recovery, especially in combination with testosterone as part of a testosterone/cortisol ratio, a used indicator of anabolic-catabolic balance (Soler-López et al., 2024). Overall, multifaceted approach of markers would align with the NIM, emphasizing the dynamic interplay of physiological and psychological processes (Thayer & Lane, 2000).

Third, the individual variability in both vmHRV and SVs means the measurement of both is crucial for future athlete monitoring. Both vmHRV and SVs should be interpreted against individualized baselines rather than generic thresholds, as HRV reflects differences in autonomic responses (Botonis et al., 2021; Olmos et al., 2024) and certain SVs hold greater relevance for specific athletes (Hamlin et al., 2019). Individualized monitoring systems accounts for natural variations and ensures more accurate and actionable insights.

As a last note, wearable technology offers promising applications for real-time monitoring of vmHRV and SVs. By offering immediate feedback, wearables bridge the gap between research and practice, enabling practical applications (Plews et al., 2017). With half of the included studies published between 2020 and 2024, interest in integrating physiological and psychological variables into athlete monitoring is growing (Thorpe et al., 2016). In fact, apps such as HRV4Training, EliteHRV, or ithlete™ have already integrated both vmHRV and SVs, demonstrating how consumer-grade technologies can support such monitoring. This evolution is also evident in the expanding examination of HRV beyond resting measures, particularly in exercise-based monitoring (Tanner et al., 2024). Thereby, the present scoping review provides a scientific foundation, and practical guidelines and suggestions, for advancing these tools.

In summary, this review supports the integration of vmHRV and SVs measures as a more comprehensive approach to athlete monitoring, capturing both physiological and psychological dimensions. Given that athletes respond to training loads differently, and away from seeking a single conclusive marker (Halson, 2014; Lac & Maso, 2004; Schmitt et al., 2013a), future systems should prioritize combining these metrics in user-friendly ways that consider individual variability and contextual factors (Bourdon et al., 2017; Filaire et al., 2003; Halson, 2014; Saw et al., 2016; Schmitt et al., 2013b). Such systems should support personalized training monitoring, advancing athlete performance and well-being, and reducing the risk of overtraining.

Deviation from the pre-registered protocol

The protocol for this review was pre-registered on the OSF, with a few adjustments made during the process. First, articles involving interventions were excluded. While interventions can provide insights into the effects of manipulations on vmHRV and SVs, the review aimed to explore their natural relationship within the context of sports. Although this focus was clear to the authors, it was not explicitly stated in the original protocol. Excluding intervention studies allowed examining how vmHRV and SVs interact organically, without the influence of experimental manipulations. Additionally, data on the reliability and validity of SVs, other physiological markers, training and performance-related variables were extracted but ultimately excluded from the manuscript to maintain focus and adhere to the recommended word count.

Limitations and future directions

This review comes with some limitations. First, studies without direct correlations between SVs and vmHRV were excluded, ensuring focus but narrowing the review's scope. Correlations were compared primarily using p-values, which can increase type-II errors, especially in small sample sizes (Batterham & Hopkins, 2006; Quintana, 2017). Including effect sizes and thereby performing a meta-analysis could address this limitation (Schäfer & Schwarz, 2019). However, this was not feasible in the present review due to methodological heterogeneity in SV constructs and measurement protocols across studies. Attempting a meta-analysis at this stage would risk comparing conceptually distinct variables. Instead, this scoping review aimed to map the literature, establish SV categories, and provide a structured overview to support future targeted meta-analyses as the field matures. Additionally, while correlation coefficients evaluate relationship strength, methods like Bland-Altman could better assess agreement between measures (Prince et al., 2008). Second, we acknowledge that the categorization of SVs into fatigue-recovery indicators, psychological states, and sleep-related variables involves a degree of subjectivity, and alternative frameworks may also be valid. Also, some SVs were over-represented. For example, Edmonds et al. (2021) reported multiple outcomes on fatigue, perceived stress, mood, sleep quality, and muscle soreness, potentially over-relying on a limited pool of data and reducing generalizability. Non-significant correlations were only reported when explicitly mentioned, suggesting potential reporting bias if some results were omitted from figures or text. Third, there was also an overrepresentation of female participants, potentially biasing findings due to known gender differences in RMSSD (Koenig & Thayer, 2016). Future studies should address these issues by recruiting larger, more balanced samples in terms of gender, as well as explore generalizability to other fit populations, such as military personnel, firefighters, or disciplines without competition, like yoga. Fourth, regarding guidelines, this review adhered to PRISMA-ScR and aligned with prior recommendations (Sabiston et al., 2022), except that no formal stakeholder consultation was conducted. Consulting other experts and practitioners in future research could enhance the relevance and applicability of findings within the field. Fifth, while the review deliberately focused on RMSSD-based vmHRV measures, the exclusion of other vmHRV parameters, such as $HFms^2$, due to their greater susceptibility to respiratory influences, may have narrowed the scope of the review. Future studies could consider including these additional measures to provide a more comprehensive perspective. Finally, theoretical issues were evident, with studies often lacking frameworks and using variable protocols. These inconsistencies limited the robustness of the research base. Future research should adopt relevant vmHRV theories (NIM and Vagal Tank Theory) and adhere to methodological guidelines.

Conclusion

This scoping review explored the relationship between vmHRV and SVs in athletes, focusing on their complementary role in monitoring training adaptations. Although some consistent correlations were found between vmHRV and SVs, such that higher vmHRV was showed associations with improved recovery, better sleep, and lower fatigue or stress, most results were largely inconsistent. These discrepancies seemed to stem from both individual and contextual factors (e.g., training status, perception biases), highlighting the need for personalised baselines and context-sensitive interpretations that include both physiological and psychological markers to capture distinct yet complementary dimensions of athlete readiness and adaptation. Moreover, the review also identified critical gaps in methodological standardization, including inconsistencies in data collection, definitions, and interpretation. To address these issues, it proposes a guideline for conducting research on SVs and vmHRV in sports settings, aiming to improve comparability across studies. From a practical perspective, the findings support the development of real-time, multifactorial monitoring systems to provide a complete understanding of athlete's states within the broader context of their lives. Future research should harmonise methodologies, expand to diverse athletic populations, and explore additional physiological markers like cortisol. Overall, this review aims to advance precise, evidence-based training systems, reducing overtraining risks while improving performance and well-being.

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Data availability: The data supporting the findings of this study are available within the article and its supplementary materials. Additionally, the datasets generated during and/or analysed during the current study are available in the Open Science Framework repository, [https://osf.io/utxb3/?view_only=003f745f9b2f43119b99b751ea75e532]

Authors contributions: CA and SL conceptualized the objectives and scope of the review. CA conducted the literature search and screening. Data extraction was performed by CA and VH. Methodological quality and consistency were evaluated by CA, VH, and SL. CA and VH analysed and synthesized the results with feedback from SL. CA and SL drafted the initial manuscript, and VH, LC, and MA provided critical revisions to subsequent versions. All authors read and approved the final manuscript.

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Note: *References marked with an asterisk (*) indicate studies included in the scoping review.*

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