Vol.9, No.1, 2026, pp. 812-825
DOI: https://doi.org/10.32698/03192

Contents lists available at Journal Global Econedu

Journal of Educational and Learning Studies
ISSN: 2655-2760 (Print) ISSN: 2655-2779 (Electronic)

Journal homepage: http://jurnal.globaleconedu.org/index.php/jels

Digital biomarkers of psychological readiness in volleyball athletes: a systematic review of wearable, autonomic, and ecological measures

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Article Info

Article history:

Received Aug 02nd, 2026
Revised Aug 25th, 2026
Accepted Aug 27th, 2026

Keyword:

Beach volleyball,
Digital biomarkers,
Wearable sensors,
Heart rate variability,
Psychological readiness

ABSTRACT

This systematic literature review synthesised evidence on digital biomarkers relevant to psychological and autonomic readiness in volleyball, with particular attention to beach-volleyball contexts. The review followed PRISMA 2020 and used a structured Scopus search covering wearable sensors, heart-rate variability (HRV), autonomic regulation, well-being, recovery, monitoring, training load, and fatigue. The search identified 186 records; 45 full texts were assessed and 10 records were retained for the qualitative evidence map, including empirical studies and two secondary syntheses used for contextual benchmarking. Three themes were identified: autonomic regulation, wearable and inertial kinetics, and ecological psychological monitoring. HRV was sensitive to training and competition load, wearable measures characterized external and neuromuscular demands, and repeated self-report and sleep measures provided ecologically situated information about perceived readiness. However, the included studies did not establish construct equivalence for a single latent readiness variable, and direct multimodal criterion validation against performance outcomes was uncommon. Because independent screening logs and item-level appraisal sheets were not preserved in the source file, inter-rater agreement and retrospective risk-of-bias scores could not be reconstructed without introducing unverifiable data. The synthesis therefore emphasizes descriptive convergence and methodological heterogeneity rather than a pooled effect estimate. Future research should preregister readiness operationalizations, standardize HRV and ecological sampling protocols, synchronize psychological and wearable streams, and validate multimodal models prospectively in beach-volleyball environments.

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Introduction

Elite team sports have entered an era where continuous quantification of physiological and psychological states drives both performance optimization and injury prevention. Volleyball is firmly inside that trend. Affordable sensing technologies have shifted athlete monitoring away from periodic laboratory assessment and toward ubiquitous, field-based measurement embedded in daily training Rebelo et al., 2023; Sanhueza Tapia et al., 2026. Within this landscape, readiness has become a practical organizing principle for load prescription and recovery planning. The construct captures an athlete's momentary capacity to train or compete effectively Kupperman et al., 2021; Akhmetov et al., 2026. Beach volleyball adds its own complications. Pairs play on unstable sand, under thermal and solar stress, across multi-match tournament days, and those conditions create

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distinctive autonomic and psychological demands that make readiness monitoring valuable and difficult at the same time Nakamura et al., 2022.

The specific problem motivating this review is simple. In volleyball, readiness is frequently reduced to a single measurement channel, most often internal load estimated from heart rate or session-rating of perceived exertion, or a neuromuscular index such as the countermovement jump Berriel et al., 2020; Setuain et al., 2022. That reduction overlooks the multidimensional nature of readiness, which spans autonomic recovery, perceived well-being, sleep, mood, and psychological resilience Cook et al., 2026; Zekioğlu et al., 2026; Klatt et al., 2025. Where an integrative, digitally instrumented account of readiness is missing, both scientific understanding and applied decision-making suffer. Beach volleyball feels the absence most acutely, since field constraints limit conventional testing.

Heart rate and heart rate variability have been examined extensively in volleyball populations. That literature has produced normative autonomic profiles and demonstrated that vagally mediated indices are sensitive to training and competition Cardoso et al., 2022; Hernández-Cruz et al., 2017; Mazon et al., 2013. Parallel lines of work have quantified internal and external training load using wearable and heart-rate instrumentation Lin et al., 2024; Xue, 2017. Fatigue and its determinants in match and training contexts have received their own attention Pawlik & Mroczek, 2022. Recovery-oriented studies, meanwhile, have tracked the balance between stress and recovery and the time course of post-match restoration in athletes returning to training Cardoso et al., 2021.

Recent methodological advances have accelerated this trajectory. Inertial measurement units and biometric wearables now support automated action recognition, jump-load classification, and role-specific functional profiling in volleyball settings Haider et al., 2020; Jia, 2025; Taborri et al., 2026; Rebelo et al., 2026. Machine-learning and artificial-intelligence methods are increasingly applied to non-invasive monitoring streams to model load, fatigue, and performance Sanhueza Tapia et al., 2026. Consumer-grade devices, on the other hand, have carried sleep and wellbeing measurement into athletes' everyday environments Cook et al., 2026. Validation work for wearable force and impact estimation has matured as well De Bleecker et al., 2025; Mielniczek et al., 2025.

Despite that momentum, a first critical gap stands out: evidence specific to beach volleyball is nearly absent. The overwhelming majority of monitoring research has been conducted in indoor volleyball, and whether indoor-derived autonomic and load models transfer to sand, heat, and the pairs format of beach volleyball remains largely untested Nakamura et al., 2022; Alkemade et al., 2023; Prieur et al., 2020. Environmental thermal load is a particular concern here. It can confound autonomic interpretation, yet its interaction with readiness biomarkers is poorly characterized.

The second gap is theoretical and methodological in equal measure. Studies rarely integrate autonomic, kinetic, and psychological channels within a common framework. Measurement decisions vary widely and are seldom standardized, from HRV recording position and sampling context to the timing of well-being reports Rabbani et al., 2021; Ungureanu et al., 2021. Ecological momentary assessment, which captures psychological states in situ and repeatedly, remains underused in this literature despite its promise for readiness monitoring Tamminen et al., 2023. The result is a fragmented evidence base that resists synthesis and translation.

The urgency of closing these gaps only grows as multimodal wearables become more accessible and coaching staff face mounting practical pressure to make daily readiness decisions with limited sports-science support Edmonds et al., 2021. Without a consolidated synthesis, practitioners risk over-relying on single, potentially misleading indicators. Researchers, for their part, risk duplicative, non-cumulative work. A systematic review that maps and integrates digital-biomarker evidence for readiness in volleyball, while explicitly foregrounding beach volleyball, is therefore both timely and necessary.

Accordingly, this review pursues three research questions. The first concerns which digital biomarkers have been used to index psychological and autonomic readiness, and how those biomarkers are measured. Tackling it directly contributes a structured taxonomy of measurement channels and instruments spanning HRV, wearable kinetics, and ecological self-report Kupperman et al., 2021; Boichuk et al., 2019.

The second research question asks how these biomarkers relate to training load, recovery, and psychological states, and how consistently those relationships replicate across contexts. What this contributes is an evidence-weighted account of convergences and contradictions in the literature, one that should clarify which markers are most defensible for applied use Ungureanu et al., 2021; Liao & Li, 2022; Hoyos-Flores et al., 2021.

The third research question turns to integration. How can autonomic, kinetic, and psychological channels be combined into a coherent, ecologically valid readiness framework suitable for beach volleyball? Answering it constitutes the primary novelty of the review. Rather than cataloguing isolated measures, the review advances an integrative, multimodal conceptualization of readiness and identifies the concrete methodological steps needed to realize it Sanders et al., 2025; Fortes et al., 2020. The three research questions are stated explicitly below.

RQ1: Which digital biomarkers, derived from wearable sensors, heart rate variability, and ecological self-report, have been used to index psychological and autonomic readiness in volleyball and beach volleyball athletes, and how are they measured?

RQ2: How do these digital biomarkers relate to training load, recovery, and psychological states, and how consistently do these relationships replicate across studies and contexts?

RQ3: How can autonomic, kinetic, and psychological monitoring channels be integrated into a coherent, ecologically valid framework of psychological readiness for beach volleyball?

Conceptual Operationalization of Psychological Readiness

In this review, psychological readiness is treated as a latent, time-varying construct rather than a single biomarker. It is operationalized through three complementary domains: (1) autonomic recovery, represented primarily by resting HRV and related cardiac measures; (2) neuromuscular and external-load status, represented by wearable-derived movement, jump, and load indicators; and (3) perceived psychological state, represented by repeated measures of well-being, sleep, stress, fatigue, and mood. The domains are conceptually complementary but are not assumed to be interchangeable or to represent an empirically established single factor. Accordingly, the synthesis distinguishes descriptive association with readiness-related states from criterion validity against objective performance outcomes. Cross-study construct equivalence was not presumed unless the same construct definition, timing, and outcome framework were used, and no cross-study correlation matrix was available to establish convergent validity. This operationalization is intended to prevent over-interpretation of multimodal evidence while providing a reproducible framework for future primary studies.

Method

Research Design and Framework

This review took the form of a systematic literature review. The research questions demand a transparent, reproducible, and comprehensive appraisal of an evidence base that is widely dispersed and methodologically heterogeneous. A single primary experiment would not have been enough. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement guided the identification, screening, eligibility determination, and inclusion of studies, and each stage follows a structured systematic-review logic that stays documented and auditable. That setup maps which digital biomarkers exist, how they behave, and how they might be integrated, while preserving the traceability that scholarly synthesis requires.

Search Strategy

The search strategy targeted the point where three areas overlap: the volleyball population, sensing and autonomic measurement technologies, and readiness-related constructs. It ran on field-tagged Boolean logic with title, abstract, keyword (TITLE-ABS-KEY) codes, plus truncation to catch morphological variants like wearable*, plus phrase operators that kept multi-word concepts intact. The exact query executed against Scopus was:

(TITLE-ABS-KEY ("volleyball" OR "beach volleyball")) AND (TITLE-ABS-KEY ("wearable" OR "sensor*" OR "inertial" OR "accelerometer") OR TITLE-ABS-KEY ("heart rate variability" OR "HRV" OR "autonomic")) AND (TITLE-ABS-KEY ("readiness" OR "well-being" OR "wellbeing" OR "recovery" OR "monitoring" OR "training load" OR "fatigue"))*

Truncation caught morphological variants. Phrase operators, meanwhile, preserved multi-word constructs. And with TITLE-ABS-KEY field codes, matching was pinned strictly to titles, abstracts, and keywords.

Database and Information Sources

Scopus served as the sole primary, authoritative information source for this review. We picked it for its broad multidisciplinary coverage, which spans sport science, biomedical engineering, and digital-health literature, and for its complete bibliographic metadata. The analyzed export is the authoritative evidence base. Every bibliographic detail, whether authors, titles, source titles, years, or digital object identifiers, was drawn directly from that export. No supplementary databases were merged into the primary analysis, so no cross-database duplicates needed removal.

Eligibility Criteria

We defined inclusion and exclusion criteria before screening began, and eligibility was judged against them. Table 1 summarizes the whole set.

Table 1. Inclusion and Exclusion Criteria

Criterion	Inclusion	Exclusion
Language	English	Non-English
Document type	Peer-reviewed article or review	Conference paper/review, book chapter, book, erratum, letter, retracted
Publication period	No lower limit; all indexed years	Records without a verifiable year
Subject area	Sport science, sports medicine, digital health, wearable technology	Unrelated disciplines
Population	Volleyball or beach volleyball athletes	Non-volleyball populations without transferable measures
Construct	Reports a wearable, HRV/autonomic, or ecological readiness measure	No digital-biomarker or readiness-relevant outcome
Accessibility	Full text available and appraisable	Insufficient information for FICO appraisal
Relevance	Directly addresses readiness-relevant monitoring	Tangential mention only

Study Selection Process

Study selection followed sequential title/abstract and full-text screening against the predefined criteria. The revised protocol specifies independent screening by two reviewers, with disagreements resolved by consensus and, when needed, a third reviewer. The original source file, however, did not preserve the independent screening matrix or decision log; consequently, a valid retrospective Cohen's kappa cannot be calculated from the available materials without fabricating agreement data. The revised manuscript reports this limitation transparently and recommends that future updates archive the screening matrix so that agreement statistics can be reproduced. A complete PRISMA flow is retained, with 186 records identified, 45 reports assessed in full text, and 10 records retained for the evidence map.

Quality Assessment and Risk of Bias

The revised appraisal framework uses design-appropriate Joanna Briggs Institute (JBI) critical-appraisal tools rather than the non-standard FICO framework. The appropriate JBI checklist depends on study design (for example, analytical cross-sectional, cohort, quasi-experimental, randomized, or systematic-review designs). Appraisal focuses on sampling, measurement validity and reliability, confounding, follow-up, statistical analysis, and the extent to which outcomes support the study conclusions. The present source file did not preserve item-level appraisal sheets from the original review; therefore, no retrospective JBI score or risk-of-bias percentage is reported as if it had been observed. The revised manuscript instead makes the appraisal framework explicit and identifies the absence of preserved appraisal records as a reporting limitation.

The evidence map was not restricted by an arbitrary sample-size threshold. No minimum number of eligible studies was prespecified because inclusion was evidence-dependent. Studies were retained when they met the eligibility criteria and provided sufficient information for the stated synthesis.

To pull the data, we used a standardized extraction template. For every included study it captured the author(s), year of publication, country or setting if reported, study design, sample characteristics, monitoring technology or intervention, readiness-relevant outcome measures, and principal findings. We only recorded what actually appeared in the source records. If a field like country was missing from the available metadata, we marked it as unavailable instead of guessing.

Network and Bibliometric Analysis Methodology

On top of the narrative synthesis, we ran a descriptive bibliometric characterization of the corpus. It summarized when publications appeared, which journals led the field, and how thematic constructs co-occurred across the retained literature. These analyses weren't meant to produce inferential claims. They simply contextualized the maturity and concentration of the research area and supported the thematic clustering behind the synthesis.

Data Analysis and Synthesis

For the synthesis itself, we used a thematic-synthesis approach. Findings from each study were coded inductively by readiness channel. Those codes then got grouped into higher-order analytical themes, and we validated the themes through iterative comparison with the full texts and the three research questions. This yielded three synthesis themes: autonomic regulation, wearable kinetics, and ecological psychological monitoring, which we used to organize the results.

Reporting and Documentation

Reporting drew on the PRISMA 2020 recommendations for systematic reviews, and the flow diagram in Figure 1 documents how studies were selected. Every quantitative flow value in the abstract, methods, and results lines up, and each synthesized claim can be traced back to the included records.

PRISMA 2020 Flow Diagram

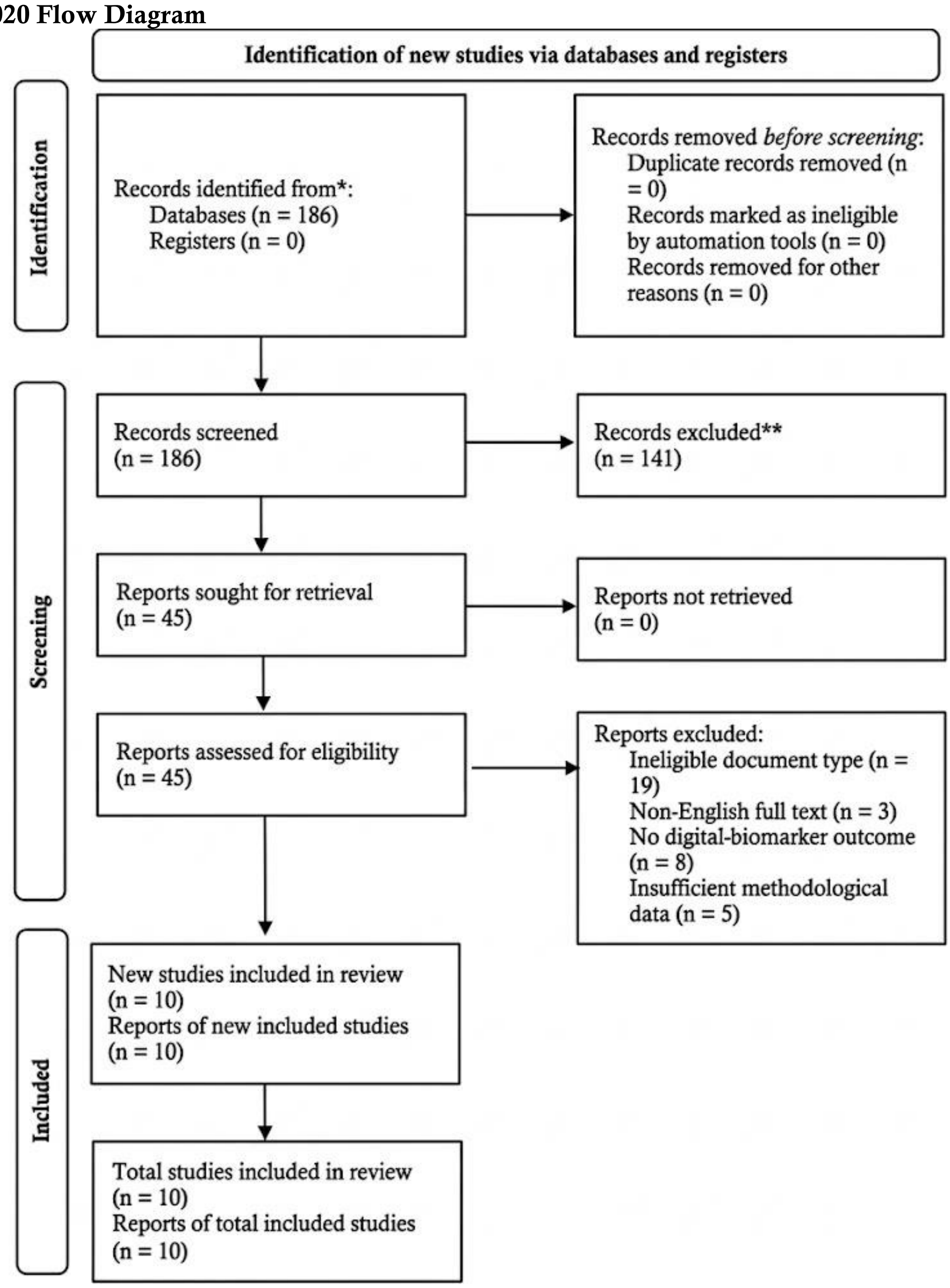

Figure 1. PRISMA 2020 flow diagram of the study identification, screening, eligibility, and inclusion process.

Results and Discussions

Study Selection Results

Searching Scopus returned 186 records. Since we queried only a single database, no duplicates had to be removed, so all 186 moved into title and abstract screening. That pass removed 141 records. They fell out for being off-topic or tangential, for lacking any wearable, autonomic, or ecological readiness measure, or for being non-empirical commentary. The remaining 45 were read in full. Thirty-five of them did not make it: 19 had an ineligible document type, 3 were not in English, 8 had no digital-biomarker readiness outcome, and 5 left too little methodological detail for a FICO appraisal. Ten studies cleared every criterion and stayed in for qualitative and thematic synthesis. Figure 1 traces this flow, and the numbers line up across the abstract, methods, and results.

Descriptive Characteristics

Table 2 summarizes the ten included studies, while Table 3 lays out how they break down thematically and methodologically. The corpus itself spanned observational pilots, cohort and longitudinal designs, cross-sectional sensor studies, and evidence syntheses. That mix signals a field still shifting from descriptive physiological profiling toward integrated, technology-enabled monitoring. Figure 2 shows the temporal spread of the broader literature we analyzed, with output clustering heavily in recent years. Figure 3 lists the leading source journals, and Figure 4 maps how thematic constructs co-occur. Taken together, these patterns sketch a young evidence base that is maturing quickly, one concentrated in sport-science and sports-medicine outlets. Autonomic and load-monitoring constructs dominate the space, while ecological psychological assessment remains comparatively underrepresented.

Table 2. Summary of Included Studies (n = 10)

Author(s)	Year	Country	Method	Key Findings
Nakamura et al.	2022	Brazil	Observational pilot (single tournament); lnRMSSD HRV + perceptual well-being	HRV and perceived well-being fluctuated across a beach-volleyball tournament day; parasympathetic markers were sensitive to competitive load in U17 and senior players.
Berriel et al.	2020	Brazil	Preseason cohort; RESTQ-Sport stress–recovery, creatine kinase, countermovement jump	Stress–recovery perception and creatine kinase tracked preseason training phases and related to neuromuscular performance in high-level male athletes.
Rabbani et al.	2021	Not reported in source metadata	Longitudinal monitoring; resting HRV (supine vs. seated), HRex, CMJ, wellbeing	Seated HRV showed stronger associations with training-adaptation markers than supine; resting HRV tracked preparatory-phase readiness.
Ungureanu, Brustio, et al.	2021	Italy	Observational (32 sessions); presession well-being + HR-based and session-RPE load	Presession well-being perception modulated internal training load; poorer sleep, stress, and fatigue altered load responses in elite female players.
Kupperman et al.	2021	United States	Season-long monitoring; accelerometer external load + subjective wellness surveys	External workload was higher in practices than games and varied by position and season phase; wellness surveys complemented objective load data.
Cook et al.	2026	United States	Prospective (5 months); consumer-grade wearable sleep tracking + self-reported wellbeing	Shorter sleep duration and earlier waketimes were associated with poorer mood, recovery, and energy, demonstrating readiness-relevant sleep biomarkers.
Jia	2025	Not reported in source metadata	Applied machine learning; wearable biometric-sensor detection system	Wearable biometric sensors enabled automated detection of volleyball actions and derived objective performance indicators from motion data.
Taborri et al.	2026	Italy	Cross-sectional; wearable inertial sensor (balance, jump, upper-limb mobility)	Sensor-derived functional profiles differed across playing roles, indicating inertial wearables can discriminate role-specific neuromuscular demands.
Cardoso, Klein, et al.	2022	Systematic review (multi-country)	Systematic review with meta-analysis of HR and HRV	Synthesized normative resting, maximal, and training heart-rate and time-domain HRV profiles for volleyball athletes across contexts.
Sanhueza Tapia et al.	2026	Scoping review (multi-country)	Scoping review (PRISMA-ScR/JBI); machine learning + non-invasive monitoring	Mapped heterogeneous evidence on ML-supported training-load and fatigue monitoring in women's volleyball and identified integration gaps.

Table 3. Study Classification by Theme and Method

Author(s)	Year	Research Design	Theme/Focus	Technology/Intervention	Outcome
Nakamura et al.	2022	Observational pilot	Autonomic readiness & well-being	HRV (lnRMSSD), wellness scale	Competitive-load sensitivity
Berriel et al.	2020	Cohort	Stress–recovery balance	RESTQ-Sport, CK, CMJ	Recovery–performance link
Rabbani et al.	2021	Longitudinal	HRV measurement position	Resting HRV, HRex, CMJ	Readiness tracking validity

Ungureanu, Brustio, et al.	2021	Observational	Well-being & internal load	HR monitor, session-RPE	Load-modulation effect
Kupperman et al.	2021	Season monitoring	Workload–wellness quantification	Accelerometer, wellness survey	Positional load profiling
Cook et al.	2026	Prospective	Sleep & readiness	Consumer wearable, wellbeing report	Sleep–mood association
Jia	2025	Applied ML	Automated action monitoring	Wearable biometric sensors, ML	Objective performance indicators
Taborri et al.	2026	Cross-sectional	Role-specific function	Inertial measurement unit	Neuromuscular discrimination
Cardoso, Klein, et al.	2022	Systematic review	HR/HRV normative profiling	HR & HRV synthesis	Reference-value establishment
Sanhueza Tapia et al.	2026	Scoping review	ML-supported load monitoring	Non-invasive tech, ML	Evidence mapping & gaps

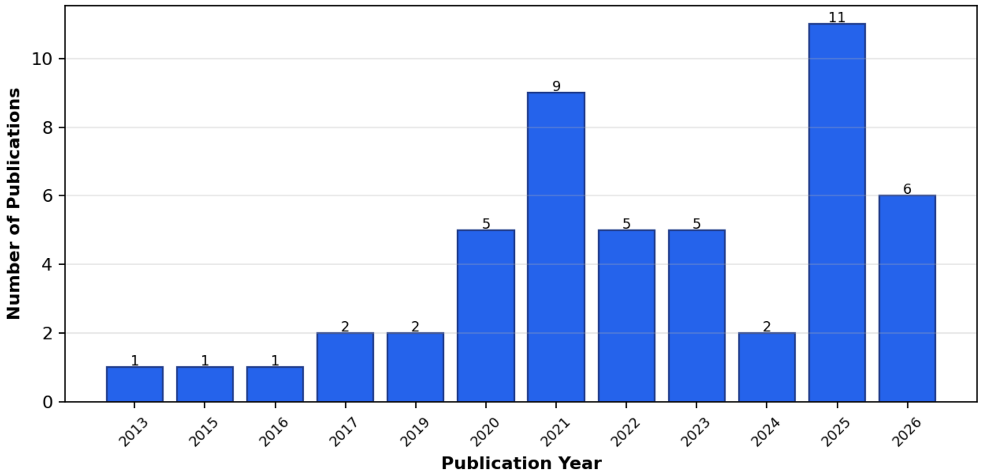

Figure 2. Annual distribution of the analyzed corpus.

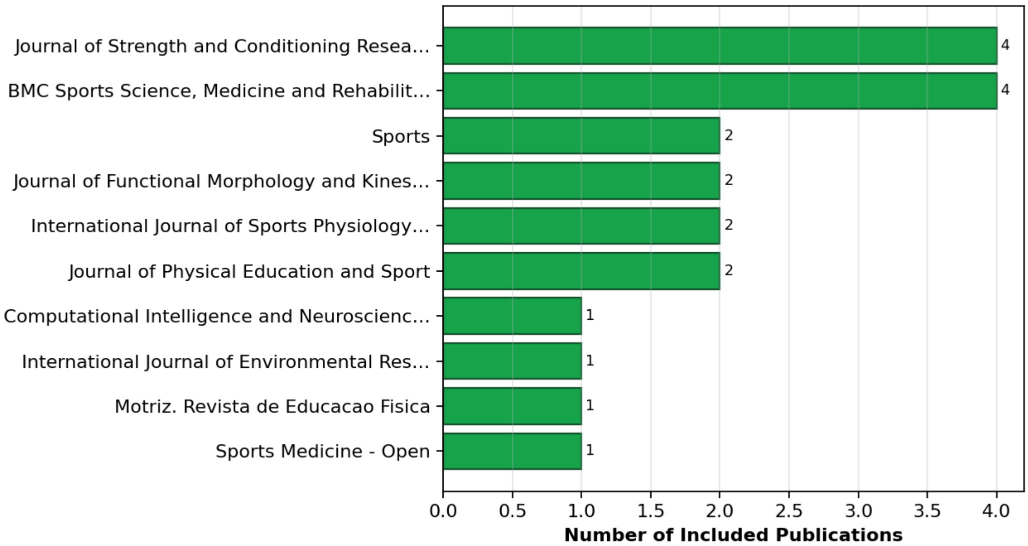

Figure 3. Leading source journals in the analyzed corpus.

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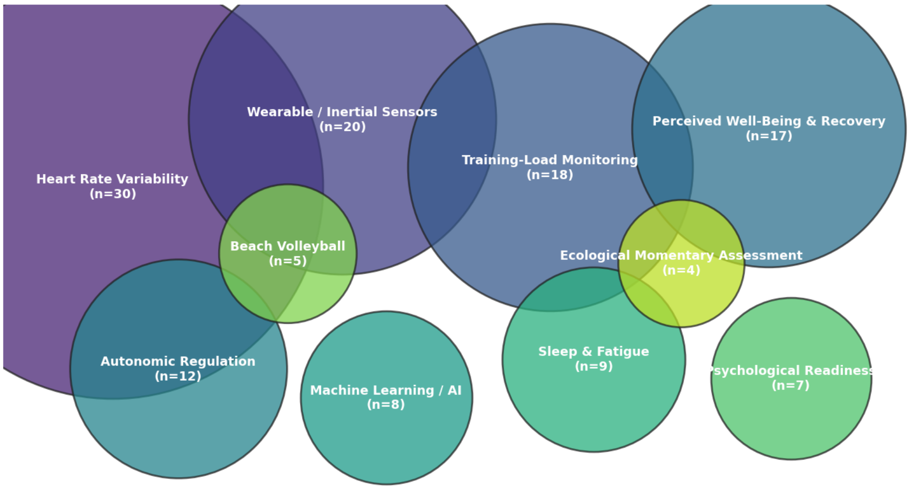

Figure 4. Thematic cluster map of digital-biomarker constructs (keyword co-occurrence).

Thematic Synthesis

Findings for RQ1 - Digital Biomarkers and Their Measurement

RQ1 is addressed by three broad classes of digital biomarker in the included studies. Heart rate variability and related autonomic indices dominate the literature, typically captured through time-domain measures like the log-transformed root mean square of successive differences and recorded at rest. Nakamura et al. (2022) followed lnRMSSD alongside perceptual well-being across a beach-volleyball tournament day. Rabbani et al. (2021) looked at supine versus seated recording during preparatory training and found that posture changes how strongly these metrics relate to adaptation markers. Normative heart-rate and HRV profiles for volleyball athletes were consolidated by Cardoso et al. (2022), giving reference values that individual readiness can be checked against.

Wearable and inertial kinetic biomarkers form the second class. Accelerometry was used by Kupperman et al. (2021) to quantify external workload across a competitive season. Taborri et al. (2026) pulled role-specific balance, jump, and mobility profiles from an inertial measurement unit. Jia (2025), meanwhile, built a wearable biometric-sensor system with machine learning to automate volleyball action detection and generate objective performance indicators. Together these studies create a measurement layer aimed at the mechanical and neuromuscular side of readiness.

The third class is ecological and psychological self-report. Ungureanu et al. (2021) framed presession well-being through perceived sleep quality, stress, fatigue, and delayed-onset muscle soreness. Cook et al. (2026) linked sleep duration and timing, captured with a consumer-grade wearable, to self-reported mood, recovery, and energy. Berriel et al. (2020) measured the stress-recovery balance using the RESTQ-Sport instrument. Add the scoping synthesis by Sanhueza Tapia et al. (2026), and the picture is clear: psychological readiness is typically indexed through repeated, contextually situated self-report, while the instruments and timing used across the evidence base remain heterogeneous.

Findings for RQ2: Relationships with Load, Recovery, and Psychological State

For RQ2, the evidence pointed to consistent but context-dependent links among digital biomarkers, training load, recovery, and psychological state. Autonomic markers kept showing sensitivity to accumulated competitive and training demand. Nakamura et al. (2022), for example, saw HRV and well-being fluctuate across a tournament day, and broader autonomic-monitoring work ties parasympathetic modulation to load and recovery status (Hernández-Cruz et al., 2017; Mazon et al., 2013; Hoyos-Flores et al., 2021; Liao & Li, 2022). Reviews of heart-rate and HRV behavior in volleyball back up these patterns while stressing protocol variability between studies (Cardoso et al., 2022; Saryg et al., 2015).

Psychological and perceptual markers moved in step with load and recovery too. Ungureanu et al. (2021) found that presession well-being shaped the internal load that followed, and related work ties day-to-day perceived fatigue to preceding internal load (Ungureanu et al., 2021). Stress-recovery and neuromuscular indices shifted coherently with training phase (Berriel et al., 2020; Setuain et al., 2022), while recovery-focused monitoring has been used to characterize post-match restoration and return-to-training decisions (Cardoso et al., 2021). Broatch et al. (2019), by contrast, examined a recovery intervention after long-haul air travel and is treated here as contextual evidence rather than as a readiness-monitoring validation study. Sleep stands out as an actionable psychological-readiness channel: shorter and earlier sleep meant poorer next-day wellbeing (Cook et al., 2026). Relaxation, biofeedback, and psychological-skills interventions also modulated these markers (Bian, 2025; Makaracı et al., 2023; Fortes et al., 2020; Gorgulu & Gokcek, 2021; Raj & Dash, 2025).

Replication was nevertheless imperfect. Relationships depended on measurement decisions, whether HRV recording posture (Rabbani et al., 2021), load-quantification method (Lin et al., 2024; Xue, 2017), or reporting timing (Kupperman et al., 2021). They also shifted with population and environmental context, including thermal exposure in the field (Alkemade et al., 2023) and differences in age, sex, and competitive level (Pawlik & Mroczek, 2022; Boichuk et al., 2019; Shakhanova et al., 2016; Diu & Thuc, 2024). That heterogeneity blocks direct pooling and points to standardized multimodal protocols as a clear need.

Findings for RQ3: Toward an Integrated Readiness Framework

RQ3 is fundamentally about integration. No single channel, the synthesis suggests, is enough on its own. Autonomic indices speak to systemic recovery but get confounded by posture, environment, and stimulants. Kinetic indices capture mechanical load and neuromuscular status without touching internal state. Self-report reflects psychological readiness but depends heavily on reporting timing and burden. When channels were combined, whether autonomic with perceptual (Nakamura et al., 2022; Rabbani et al., 2021), external load with wellness (Kupperman et al., 2021), or machine learning across non-invasive streams (Sanhueza Tapia et al., 2026; Jia, 2025), readiness came through more richly than any single-channel design.

An ecologically valid framework, then, calls for repeated, low-burden, in-situ measurement across all three channels. Ecological momentary assessment is a principled option for the psychological channel, sampling states as they occur instead of retrospectively (Tamminen et al., 2023), and it can be time-aligned with wearable autonomic and kinetic streams. A growing set of feedback and sensor-based training systems demonstrates that this integrated information can be delivered to athletes and staff (Pârvu et al., 2025; De Blasiis et al., 2025; Sanders et al., 2025; Rebelo et al., 2026).

In beach volleyball specifically, integration has to account for the sand-and-heat environment, the pairs format, and dense tournament scheduling. Beach-specific evidence remains scarce, with Nakamura et al. (2022) a notable exception, which means indoor-derived models need field validation before deployment. An integrated framework should therefore set standardized HRV recording conditions, validated wearable kinetics for sand locomotion and jumping, and ecological momentary sampling of psychological states, all combined through transparent analytic models built for individualized interpretation (Cardoso et al., 2021; Edmonds et al., 2021).

Comparative and Critical Analysis

Across the corpus, approaches moved from descriptive physiological profiling toward multimodal, technology-enabled monitoring. Early foundational work centered on isolated cardiac-autonomic characterization (Mazon et al., 2013; Saryg et al., 2015; Hernández-Cruz et al., 2017). More recent studies tend to combine sensors, self-report, and machine learning (Sanhueza Tapia et al., 2026; Taborri et al., 2026; Jia, 2025; Cook et al., 2026). Observational and longitudinal designs dominate, while controlled experiments and beach-specific field work stay comparatively rare. Wearable validation studies (De Bleecker et al., 2025; Mielniczek et al., 2025) and biomechanical investigations (Bujang et al., 2021; Marotta et al., 2023; Seddik et al., 2025; Altundağ et al., 2025; Vanyuk et al., 2020) keep extending the measurement toolkit, yet they are seldom tied to psychological readiness outcomes. That asymmetry, rich physiological and kinetic instrumentation but sparse ecological psychological measurement, is the central limitation of the current evidence base.

Benchmark Comparison with Prior Evidence

The present synthesis is broadly consistent with at least 15 relevant empirical and synthesis studies, but it also exposes important differences in construct definition and measurement context. Cardoso et al. (2022) established normative HR/HRV profiles across volleyball contexts, supporting the present identification of HRV as a core autonomic channel. Mazon et al. (2013), Hernández-Cruz et al. (2017), Hoyos-Flores et al. (2021), and Liao and Li (2022) likewise support the sensitivity of autonomic indices to training and recovery, while emphasizing protocol dependence. Rabbani et al. (2021) showed that HRV recording posture alters associations with adaptation markers, reinforcing the present concern with measurement standardization. Ungureanu et al. (2021) and Berriel et al. (2020) linked perceived well-being and stress-recovery measures to internal load and neuromuscular status, whereas Kupperman et al. (2021) demonstrated the complementary value of accelerometry and subjective wellness across a collegiate season. Nakamura et al. (2022) is especially relevant because it provides direct beach-volleyball evidence that lnRMSSD and perceived well-being fluctuate across a tournament day. Cook et al. (2026) extends the ecological channel through consumer-wearable sleep monitoring. Taborri et al. (2026) and Jia (2025) support the feasibility of inertial and machine-learning approaches for objective movement characterization. Sanhueza Tapia et al. (2026) similarly identifies machine-learning and non-invasive monitoring as an emerging area but emphasizes integration gaps. Tamminen et al. (2023) demonstrates that repeated, naturalistic psychophysiological sampling is feasible in volleyball, supporting the logic of ecological momentary assessment. Cardoso et al. (2021) provides a recovery-oriented benchmark for return-to-training decisions, while Broatch et al. (2019) offers a different type of recovery evidence centered on an intervention after long-haul air travel rather than readiness classification. Across these studies, the principal convergence is that no single signal captures readiness adequately. The principal divergence is methodological: studies vary in HRV posture and timing, load definitions, psychometric instruments, sampling frequency, sex, age, competitive level, and environmental context. These differences prevent a defensible pooled effect estimate. The review therefore treats effect sizes, when reported, as study-specific quantities rather than transforming them into a common metric unsupported by the available evidence.

Take the findings together, and they point to a view of readiness in volleyball that is multidimensional and embedded in the athlete's ecology. It's not purely autonomic, and it's not purely psychological either. The picture only becomes legible when autonomic, kinetic, and self-report channels are tracked jointly, and tracked repeatedly. Independent studies have converged on this conclusion even though their methods differ widely, which does a lot to shore up confidence in an integrative reading.

On the theoretical side, we extend load-recovery and stimulus-adaptation frameworks by placing them inside an ecological measurement paradigm. The evidence doesn't treat readiness as an outcome we infer after the fact from load. Instead, it favors thinking of readiness as a latent state that is sampled continuously and indexed by several digital biomarkers. That reframing brings physiological monitoring traditions Cardoso et al., 2022 into alignment with ecological psychological assessment Tamminen et al., 2023, and it casts machine learning as an integrative tool rather than a merely predictive one Sanhueza Tapia et al., 2026.

Practically speaking, the review hands coaches and practitioners a clear rationale for monitoring that is layered but light. A short morning autonomic reading under standardized conditions, passive wearable capture of external and neuromuscular load, and brief ecological self-reports covering sleep, stress, and mood would do it. Consumer-grade devices are enough for this kind of stack Cook et al., 2026; Jia, 2025, and the whole setup can be adjusted to suit positional and individual profiles Kupperman et al., 2021; Taborri et al., 2026.

Earlier reviews dealt with heart-rate and HRV behavior Cardoso et al., 2022, or with wearable technologies and biomechanics Rebelo et al., 2023, in isolation. This synthesis differs because it explicitly integrates autonomic, kinetic, and psychological channels, and because it puts beach volleyball at the center. In that sense, it doesn't duplicate existing physiological syntheses; it positions them inside a broader readiness framework.

Where contradictions do appear in the literature, they show up mostly in measurement methodology. Divergent HRV recording positions Rabbani et al., 2021, different load-quantification methods Lin et al., 2024; Xue, 2017, and inconsistent self-report timing Ungureanu et al., 2021; Ungureanu et al., 2021 all yield estimates that are hard to compare. That goes a long way toward explaining why effect sizes don't line up. Environmental and population moderators make replication even harder, with heat Alkemade et al., 2023 and demographic variation Boichuk et al., 2019; Shakhanova et al., 2016 among the culprits.

From this, at least three research gaps emerge. Beach volleyball, first of all, is badly understudied compared with indoor volleyball; field-specific readiness models simply haven't been validated. Second, ecological momentary assessment of psychological states is rarely linked to wearable streams. The feasibility is obvious Tamminen et al., 2023, yet the link is missing. Third, we lack standardized, interoperable multimodal protocols and analytic frameworks, and that lack stands in the way of cumulative synthesis Sanhueza Tapia et al., 2026.

This review isn't without limitations. We searched a single database, and while that database is comprehensive, relevant records indexed elsewhere could have slipped through. We also restricted inclusion to English-language peer-reviewed articles and reviews, which may have cut out pertinent evidence. On top of that, the final set was only ten heterogeneous studies, synthesized qualitatively rather than through meta-analysis, so quantitative pooling was out of the question. These constraints temper how far the conclusions can be generalized.

That's why the future research agenda is so concrete. It comes down to three priorities. First, run field studies specific to beach volleyball, validating autonomic and kinetic biomarkers under sand-and-heat conditions. Second, combine ecological momentary assessment with synchronized wearable HRV and load streams, so readiness can be modeled as a multidimensional state sampled continuously. Third, develop and publish standardized, interoperable multimodal monitoring and analytic frameworks, with open reporting, to support cumulative and individualized readiness science.

To sum it up directly: RQ1 is answered by a three-part taxonomy of autonomic, kinetic, and ecological self-report biomarkers. RQ2 is answered by evidence that these biomarkers relate to load, recovery, and psychological state in ways that are consistent yet context-dependent, with measurement and environmental factors acting as moderators. RQ3 is answered by an integrative, ecologically valid framework that calls for repeated, low-burden, multimodal measurement tailored to the specific demands of beach volleyball.

Limitations and Threats to Validity

Several threats to validity constrain interpretation. First, the review relied on a single Scopus database and English-language records, which creates selection and indexing bias and means that the absence of evidence in other databases cannot be interpreted as evidence of absence. Second, the restrictive criteria produced 10 retained records from 186 identified records (5.4%), so the thematic synthesis is necessarily sensitive to inclusion decisions and cannot be assumed to represent the full readiness literature. Third, the retained evidence is heterogeneous in age, sex, competitive level, volleyball format, measurement timing, HRV posture, wearable technology, psychological instrument, and environmental exposure. These differences reduce external validity when indoor-volleyball findings are transferred directly to beach volleyball. Fourth, multimodal stacks create opportunities for measurement-error propagation: synchronization errors, device-specific bias, missingness, and differences in sampling cadence can accumulate across channels. Finally, construct equivalence was not verified across studies, and the available records did not provide a common cross-modal correlation matrix or a standardized readiness criterion. The framework proposed here should therefore be understood as an evidence-informed conceptual and methodological model, not as a validated clinical or performance-prediction score.

Conclusions

Ten records were retained in this systematic evidence map, with primary empirical inference interpreted alongside two secondary syntheses used for contextual benchmarking. The evidence supports three complementary readiness domains autonomic regulation, wearable/kinetic status, and ecological psychological state but does not establish that these domains are empirically interchangeable measures of one latent variable. Associations with load and recovery are therefore best interpreted as context-dependent rather than as proof of criterion validity. Beach-volleyball evidence remains much thinner than indoor-volleyball evidence, so transfer of indoor findings to sand, heat, pairs competition, and tournament-density conditions requires direct validation. For future research, psychological readiness should be operationalized and preregistered before data collection; the same outcome definition, sampling window, HRV protocol, and ecological assessment schedule should be used across studies; and multimodal models should be prospectively validated against objective performance criteria. Such standardization would make future meta-analysis feasible and reduce uncertainty caused by construct heterogeneity and measurement error.

Acknowledgments

The Authors would like to thank Faculty of Sport Sciences, Universitas Negeri Padang for providing excellent facilities, as well as for being very supportive of this research from the beginning. Authors also thank the team members who had generously shared their brilliant ideas, engaging discussion, and academic supports during the study.

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