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TELEMEDICINE AND REMOTE MONITORING IN SPORTS MEDICINE: CURRENT APPLICATIONS, DIAGNOSTIC POTENTIAL AND FUTURE DIRECTIONS

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1. ABSTRACT

BACKGROUND

Telemedicine and remote physiological monitoring are increasingly used in sports medicine, but their clinical value, limitations, and integration into decision making processes remain insufficiently defined.

AIMS

To provide a structured analysis of telemedicine and remote monitoring in sports medicine, focusing on clinical applications, diagnostic potential and limitations, interpretation of remote data within clinical decision making, and organisational and ethical conditions for their implementation.

METHODS

A narrative review of literature published between 2010 and 2026 was conducted using PubMed and Google Scholar, along with clinical guidelines and regulatory documents. The search was performed using predefined keyword combinations related to sports medicine, telemedicine, and remote monitoring. Records were screened in two stages based on titles and abstracts followed by full text assessment. Sources were selected according to clinical relevance, methodological transparency, and applicability to sports medicine practice. No formal assessment of study quality or risk of bias was performed.

RESULTS

Telemedicine and remote monitoring are applied in injury assessment, rehabilitation, and return to play management, improving access and continuity of care when integrated into structured clinical pathways. However, evidence for clinical outcomes remains limited and heterogeneous. The diagnostic value of wearable derived data is constrained by variability, measurement artefacts, and lack of standardised interpretation models. Remote data contribute to clinical decision making primarily when interpreted within trend based and context dependent frameworks, while isolated parameters have limited clinical relevance and may lead to misinterpretation. Errors in interpretation may result in inappropriate load management, missed clinical deterioration, or unnecessary restriction of activity. Organisational factors, including interoperability, data governance, and regulatory frameworks, are key determinants of implementation and directly influence data availability, consistency of decisions, and continuity of care. Ethical and data protection considerations affect not only compliance but also the reliability of clinical information, as concerns regarding confidentiality may influence data reporting, adherence, and the accuracy of clinical assessment.

CONCLUSIONS:

Telemedicine and remote monitoring can support clinical decision making in sports medicine when embedded in structured pathways with clear protocols and governance. Their clinical utility is limited by variability in evidence, risks of misinterpretation, and lack of validated thresholds. Remote formats are associated with potential clinical errors, including underestimation of injury severity, missed complications, and inappropriate load management decisions. Effective use requires integration with clinical judgement, hybrid care models, and organisational frameworks that prioritise data quality, ethical use, and patient safety.

Keywords: telemedicine, sports medicine, remote patient monitoring, wearable sensors, HRV, continuous glucose monitoring, return to play, injury risk, clinical decision making, data governance

2. INTRODUCTION

Telemedicine in sports medicine is increasingly used as a clinical tool that supports assessment, monitoring and decision making beyond in person visits. In both elite and community settings, it facilitates faster communication between athletes, clinicians and coaching staff, improves access to specialist expertise and allows timely decisions on injury management and return to play. Practical implementation includes structured remote consultations, standardized documentation adapted for remote review, and predefined clinical protocols integrated into digital platforms. These elements enable continuity of care while maintaining clinical oversight and safety. [1,3,4]

The adoption of telemedicine in sports medicine depends on several practical factors. Its clinical value is determined by whether it reduces delays in assessment, supports rehabilitation and improves return to play decisions. Usability is critical, particularly the integration of telemedicine platforms with electronic records and imaging systems, which affects routine clinical workflow. In addition, organisational policies influence implementation, for example requirements for remote follow up after concussion or the use of physiological monitoring such as heart rate variability and sleep tracking. When these factors are aligned with clear clinical protocols, telemedicine becomes a stable component of care rather than an occasional solution.

Alignment of these forces with clear governance rules enables sustained telemedicine use, whereas misalignment leads to a reversion to unsystematic and ad hoc video interactions [1, 3, 4].

In athlete monitoring specifically, remote physiological data add value only when combined with a common language for interpretation and escalation. Weekly aggregates, for example HRV means and coefficients of variation, together with structured symptom check ins and objective workload proxies such as GNSS or IMU, make remote conversations actionable. Yet the visibility of these data introduces additional responsibilities related to privacy, consent for secondary use and athlete representation in data governance, and these considerations have shifted from specialist legal discussions into routine team practice. This review therefore situates telemedicine and RPM not only within clinical evidence but also within organisational realities, including interoperability, resourcing and ethical safeguards that sustain trust over time [3, 4, 29].

Telemedicine, as framed in WHO guidance, has shifted from an emergency tool to a routine element of health services [1]. In sports medicine, virtual care and RPM can improve access across performance levels, enhance continuity of rehabilitation, and support safer return-to-play pathways while streamlining multidisciplinary collaboration [2, 5].

2.1 Why Now: Dense Calendars, Data Rich Teams and Mature Governance

Competitive calendars are denser than a decade ago and travel windows are shorter, which makes in-person access to specialist care harder for many athletes. Telehealth fills those gaps by moving parts of triage, review of imaging, and rehabilitation progression to secure remote pathways. This is not a temporary pandemic artefact but a durable shift that health authorities and professional bodies have since embedded in guidance. [1,3,4,31]

At the same time, the team environment has become more data-rich. Remote heart-rate variability, sleep trends, workload from GNSS/IMU, and nutrition logs can be reviewed asynchronously before a brief video check-in. When teams agree on 'signal hygiene' (how data are captured, aggregated, and flagged) and escalation rules, remote conversations become specific and short, improving throughput without lowering safety. [3,4,8,12]

Economic and equity considerations also argue for telemedicine 'now'. Remote touchpoints reduce travel costs and time burden for amateurs and youth athletes while preserving continuity during exams, work, or caregiving. Low-bandwidth fallbacks and multilingual scripts, recommended in operational guides, make these pathways usable beyond elite settings. [1,4,5]

Finally, governance has caught up. Post-pandemic updates clarified licensure, informed-consent language, and privacy safeguards. Sports contexts added the separation of clinical care data from anti-doping compliance records and placed athlete voice in data decisions. With these guardrails in place, the remaining bottlenecks are mostly organizational, primarily involving interoperability and resourcing, rather than legal permissibility. [1,3,29,30,38]

Despite the rapid implementation of telemedicine and remote monitoring in sports medicine, there is currently no comprehensive analysis that integrates clinical aspects with data interpretation, organizational implementation, and regulatory frameworks [1,3,4,38]. Most published studies focus either on the technical characteristics of devices or on specific areas such as telerehabilitation or remote workload monitoring, without a systematic evaluation of clinical use scenarios and the limitations of these technologies [5,6,7,12]. Key issues remain insufficiently studied, including the clinical validity of parameters obtained from wearable devices, their reproducibility across different conditions, and their impact on clinical decision making in sports medicine practice [8,10,12,16]. In addition, there is no unified approach to integrating remote monitoring data into clinical algorithms and athlete management protocols [3,4,34].

The scientific novelty of this review lies in its integrated approach, examining telemedicine and remote monitoring within the context of real clinical processes in sports medicine. The review combines evidence on the diagnostic potential of these technologies with a critical analysis of their limitations, as well as considerations of interoperability, data governance, and ethical frameworks [3,4,29,42,44]. In contrast to existing publications, this review focuses on clinical applicability and practical implementation models, including protocol standardization, interpretation of physiological parameters, and the integration of remote data into treatment decisions and return to play pathways [32,34,46].

3. AIM

The aim of this review is to provide a structured analysis of the use of telemedicine and remote monitoring in sports medicine, with a focus on their clinical applicability, limitations, and conditions for integration into practice.

Research objectives

1. To describe the main clinical scenarios of telemedicine and remote monitoring in sports medicine, including injury assessment, rehabilitation, and return to play monitoring.
2. To analyze the diagnostic potential and limitations of data obtained from wearable devices and remote monitoring systems.
3. To examine the interpretation and use of remote data within the clinical process.
4. To identify key organizational and regulatory factors influencing the implementation of telemedicine and remote monitoring in sports medicine.
5. To summarize approaches to data protection and the ethical use of athlete health information.

4. METHODS

This study was conducted as a narrative review of the literature. The review aimed to synthesize and clinically interpret published data on telemedicine and remote monitoring in sports medicine without applying formal systematic review procedures.

The literature search covered publications from 2010 to 2026. Publicly accessible databases, including PubMed and Google Scholar, were used for source identification. In addition, publications from leading field journals and documents from international and professional organizations with regulatory or practical relevance were reviewed.

The search was performed using reproducible combinations of keywords, including "sports medicine", "telemedicine", "telehealth", "remote monitoring", "wearable devices", "HRV", "GNSS", "IMU", and "continuous glucose monitoring", combined using the Boolean operators AND and OR. In PubMed, the search was limited to titles and abstracts. In Google Scholar, the initial pages of results were screened, with priority given to publications in peer reviewed journals.

The initial search yielded approximately 220 records. After removal of duplicates and exclusion of irrelevant publications based on titles and abstracts, approximately 110 sources remained. Following full text assessment using the inclusion

and exclusion criteria, 55 sources were included in the final analysis.

The selection process was conducted in two stages. First, titles and abstracts were screened to exclude duplicate and irrelevant records. Second, full texts were evaluated for clinical relevance, presence of practical application details, and alignment with the aim of the review.

Inclusion criteria comprised English language publications addressing athletes across different performance levels and covering clinically or organizationally relevant aspects of telemedicine and remote monitoring, including injury prevention, rehabilitation, monitoring, and return to play decision making. Review articles, comparative studies, consensus documents, clinical guidelines, and regulatory materials were included.

Exclusion criteria included case reports without analytical synthesis, publications focused primarily on technical descriptions of devices without clinical interpretation, opinion pieces lacking sufficient evidence, and studies not directly relevant to sports medicine practice.

Sources were categorized into three groups. The first group included scientific publications used to analyze clinical effects and diagnostic capabilities. The second group included consensus documents and clinical guidelines used to evaluate standards of care and clinical protocols. The third group included regulatory and organizational documents used to analyze governance, data management, and implementation aspects.

Quality control of sources was based on publication type, peer review status, methodological transparency, and clinical applicability. Priority was given to reviews, comparative studies, and documents with clearly described methods. Publications identified through Google Scholar were additionally evaluated based on the credibility of the source and excluded if lacking indicators of scientific reliability.

The analysis focused on clinical use scenarios, diagnostic potential and limitations of technologies, as well as implementation aspects, data interpretation, and privacy considerations.

As this was a narrative review, no formal risk of bias assessment was performed. This represents a limitation of the study, as source selection and interpretation may be influenced by expert judgment.

5. RESULTS

The Results section synthesises the findings of the narrative review with a focus on practical clinical applications of telemedicine and remote monitoring in sports medicine. The results are presented thematically, encompassing models of care, diagnostic domains, interpretation of remote data, and clinical decision-making frameworks relevant to athlete management.

5.1 TELEMEDICINE MODELS IN SPORTS MEDICINE

Telemedicine in sports medicine is applied across multiple clinical scenarios that differ in terms of synchronicity, clinical objectives, and limitations of remote assessment. These models support injury triage, rehabilitation, return-to-play decision-making, and longitudinal athlete monitoring.

To provide an overview of the most common clinical applications of telemedicine and remote monitoring in sports medicine, Table 1 summarises key scenarios, data sources, clinical objectives, and criteria for escalation to in-person evaluation.

Table 1. Clinical scenarios of telemedicine and remote monitoring in sports medicine.

Clinical scenario	Type of telemedicine	Data used	Clinical objective	Limitations of remote assessment	Criteria for in person evaluation	References
Acute injury assessment	Synchronous video consultation	Visual inspection, ROM, pain, movement video	Initial triage and decision making	Lack of palpation, limited visualisation	Suspected fracture, neurological symptoms	[1, 3, 4]
Rehabilitation	Telerehabilitation	Exercise video, pain and function scales,	Monitoring progress and adjusting exercises	Limited assessment of strength and stability	Lack of progress, increased pain	[5–7]

		workload				
Return to play	Hybrid model	Functional tests, HRV, workload, symptoms	Decision making on return to activity	Lack of instrumental assessment, risk of underestimation	Symptom recurrence, unstable parameters	[32–34]
Chronic condition management	Synchronous and asynchronous	PROs, HRV, sleep, symptom diaries	Long term management and therapy adjustment	Low specificity of symptoms, reliance on self report	Clinical deterioration, new symptoms	[1, 3, 4]
Load monitoring	Remote monitoring	GNSS, IMU, HRV, sleep	Prevention of overload and load optimisation	Data variability, risk of overinterpretation	Signs of overload, decreased performance	[8–12]
Second opinions	Asynchronous review	Medical records, video, imaging	Diagnosis confirmation and management planning	Limited clinical context	Unclear diagnosis, conflicting findings	[1, 4]

5.1.1 Real time teleconsultations (video/phone): detailed workflow and use cases

Pre participation and periodic reviews. Real time teleconsultations for pre participation and periodic reviews follow a structured script: the clinician verifies identity, confirms informed consent, and uses a secure platform before reviewing medications, asthma action plans, and potential indicators of relative energy deficiency in sport (RED S). These encounters also enable proactive discussion of anticipated changes in training load or travel so that modifiable risks are addressed ahead of time [1, 3, 4].

Acute injury triage. When injuries occur away from clinic, the clinician obtains a focused remote history and performs a camera guided visual examination to assess inspection findings, weight bearing status, and basic range of motion maneuvers demonstrated by the athlete. The outcome is an explicit disposition: immediate imaging, short term protection or immobilization, or brief watchful waiting with strict, documented safety net instructions for deterioration [1, 3, 4].

Second opinions and shared return to play (RTP) decisions. Teleconsultations are well suited to second opinions and shared RTP deliberations because prior imaging, rehabilitation logs, and training notes can be reviewed on screen while the athlete performs standardised functional tasks including a single leg squat or hop, under appropriate camera placement and lighting. This supports consistent decision making across sites and time points [1, 3, 4].

Chronic condition management. Conditions such as exercise induced bronchoconstriction, IBS like symptoms, iron deficiency, or persistent sleep disturbance can be followed longitudinally through scheduled video or phone reviews. Remote patient reported outcomes and RPM dashboards support trend based adjustments while reducing travel burden and preserving continuity of care during congested competition calendars [1, 3, 4].

Minimum quality safeguards. Across all real time use cases, programmes apply common safeguards: documentation parity with in person care, verification of jurisdictional licensure, explicit deterioration and escalation plans with 24/7 contact information, data minimisation with encryption in transit and at rest, and predefined thresholds that trigger immediate in person assessment such as suspected fracture, new neurological deficit, or syncope. [1, 3, 4].

5.1.2 Store and forward (asynchronous) pathways: structure, medicolegal safeguards, and team collaboration

Structured inputs. Store and forward workflows begin with a clearly defined intake that accepts short smartphone videos such as gait, landing mechanics, or throwing technique, alongside wound photographs, patient reported outcomes, training logs, and trainer notes. Each file is time stamped and labelled to support auditability and triage [1, 4].

Triage and review cycle. After receipt, the system performs an automated completeness check and routes the case according to predefined triage rules that distinguish urgent submissions from routine reviews. A clinician then conducts a time stamped assessment and records a decision with corresponding patient notification, ensuring that each step is visible and recoverable in the record [1, 4].

Operational safeguards. To maintain quality and legal defensibility, services implement measurable service level targets for turnaround, tamper evident audit logging, least privilege, role scoped access controls, and a documented retention and deletion policy. Clear instructions for warning symptoms remain essential so that asynchronous convenience does not dilute escalation to urgent care when required [1, 4].

Multidisciplinary collaboration. A key advantage is that orthopaedics, physiotherapy, nutrition, psychology, and performance science can contribute asynchronously in a common workspace. This reduces scheduling friction and enables targeted, role appropriate input without coordinating multi party live sessions [1, 4].

Known limitations and rejection rules. Because palpation and instrumented testing are not available remotely, programmes adopt conservative thresholds for escalation to in person review. Submissions that do not meet quality criteria, poor lighting, unstable framing, or inadequate views are rejected with simple automated guidance that helps the athlete resubmit usable material [1, 4].

Documentation parity. Even when cases are managed asynchronously, documentation follows the same structure as in person care, and each decision clearly states the next step—whether to continue remotely, request clarified media or escalate to a clinic visit. This approach prevents open ended threads and ensures that necessary care is not delayed [1, 4].

5.1.3 Telerehabilitation: programme design, fidelity of remote assessment, and hybrid progression

Programme design. A telerehabilitation programme begins with a structured remote evaluation capturing pain intensity, function, and sport specific limitations using validated scales agreed in advance. Based on this baseline, the clinician prescribes an exercise plan with defined sets, repetitions, tempo, and objective progression criteria, scheduling live supervised sessions to verify technique and adjust loading. Automated reminders and simple adherence dashboards help maintain momentum and reduce missed sessions [5–7].

Fidelity of remote assessment. High quality remote assessment depends on what the camera can reliably show. Before each session, athletes receive brief instructions that standardise camera placement in frontal and sagittal planes, set an appropriate step back distance, and ensure adequate lighting so that joint angles and trunk control are visible. When functional tasks are demonstrated such as squats, step downs, hops, or landing drills, therapists use predefined cues and repeatable prompts to minimise variability across visits and enable like for like comparisons [5–7].

Hybrid progression and checkpoints. Although many elements proceed remotely, programmes incorporate targeted in person checkpoints where hands-on testing adds value for example, dynamometry, instrumented hop testing with IMUs, or palpation when symptoms plateau. These milestone visits anchor a hybrid progression in which remote blocks build capacity and on site sessions verify readiness to advance. Progression criteria combine symptom stability, functional performance, and, where available, RPM trends to avoid premature escalation [5–7].

Adherence and communication. Short, frequent touchpoints such as weekly check ins supplemented by asynchronous video reviews sustain engagement during congested training or travel periods. Simple feedback loops including annotated clips highlighting one reinforcement and one priority fix build self efficacy and reduce corrective workload in subsequent live sessions. When flares occur, clear step down rules and rapid re booking prevent loss of momentum [5–7].

Outcome tracking. Progress is documented against pre selected measures that matter clinically and operationally: joint specific scales, time loss and unplanned visits, and athlete reported confidence. Notes mirror in person structure so that remote and on site documentation remains interchangeable for audit and handover. Weekly summaries blend qualitative notes with a small set of numeric indicators to support consistent team decisions [5–7].

Practical limits and escalation. Remote delivery has recognised limits, including the absence of palpation and certain instrumented tests. Safety is protected by conservative escalation triggers, for example new neurological signs, progressive swelling, or failure to meet milestones despite good adherence, which mandate in person reassessment. The same triggers appear in the athlete’s plan to support timely self escalation [5–7].

5.1.4 Remote physiologic monitoring (RPM): protocols, thresholds, and escalation logic

Protocols and capture discipline. RPM is most effective when protocols specify device type, placement, timing, artifact criteria, and weekly aggregation rules. In practice this means capturing morning supine HRV under controlled breathing, recording nightly sleep continuously, and collecting session based inertial data with consistent sensor orientation for like for like comparisons over time [3, 4].

Baseline construction and thresholds. Decisions are anchored to athlete specific baselines with predefined “small but meaningful” change thresholds that trigger review. Rather than reacting to single day fluctuations, teams use weekly means and coefficients of variation and combine them with symptom trends so alerts reflect sustained deviation rather than noise [3, 4].

Escalation logic and conflict resolution. Escalation rules define what happens when signals diverge for example stable HRV alongside rising soreness and deteriorating sleep. In such cases, programmes prioritise clinical reassessment or conservative load adjustment before increasing intensity, reducing the risk of premature progression [3, 4].

Governance and consent scope. Because RPM involves continuous health and biometric data, consent materials must specify the primary care purpose, optional analytical layers, retention periods, and the athlete's rights, while access follows least privilege principles and is fully logged. These rules ensure accountable decision support and restrict secondary uses to explicitly permitted contexts [3, 4].

Operational reliability and feedback. Reliability is sustained by standardising naming, time stamps, and metadata at ingestion, and by providing user feedback when artifact criteria are breached or minimum capture requirements are missed. Routine quality control keeps dashboards interpretable and reduces false alarms that would otherwise erode trust [3, 4].

5.1.5 Regulatory, licensure and financing considerations: operational checklist

Legal and ethical prerequisites. Before activation, organisations verify that clinicians are licensed for the jurisdictions in which athletes are located and that telehealth specific informed consent language is in place. A privacy impact assessment is completed, and the programme executes data processing or business associate agreements with vendors, clarifying responsibilities for security, retention, and breach notification [1, 3, 4].

Clinical standards and remote examination protocols. Operations include documented, body region specific remote examination steps, red flag decision trees, and predefined escalation criteria so that teleconsultations mirror the safety and completeness of in person visits. Documentation macros preserve SOAP structure for seamless integration with existing records and handovers [1, 3, 4].

Technical safeguards and platform security. Platforms provide encryption in transit and at rest, hardened device configurations, and single sign on with multi factor authentication. Access follows least privilege, role scoped principles and is supported by immutable audit logs and a tested incident response plan [1, 3, 4].

Financing, coding, and administrative planning. The business layer defines coding and billing for tele services where reimbursement applies and a transparent cost model for RPM devices and platforms. Training plans, service level objectives (SLOs), and concise quality dashboards help maintain throughput and surface bottlenecks early in the season [1, 3, 4].

Quality and equity commitments. To avoid inequities, programmes offer language support, accessibility features, and low bandwidth fallbacks including audio first options so that athletes can use services reliably regardless of location or connectivity. Checklists and templates standardise intake, consent, documentation, and escalation pathways [1, 3, 4].

5.1.6 Socio technical adoption factors in teams and federations

Successful programmes converge on a small set of operational behaviours that make remote care predictable and safe. First, standard work is embedded directly into the digital platform, and remote visit checklists, red flag decision trees and documentation templates ensure that new clinicians deliver care consistent with established expectations from day one. Second, teams establish signal hygiene by agreeing minimum data quality rules, such as correct device placement, appropriate timing of measurements and the required number of consecutive days needed to confirm an outlier, so that discussions focus on meaningful trends rather than noise. Third, interoperability by default reduces the risk of errors because rosters, appointments, imaging links and RPM streams are integrated into shared systems rather than copied manually across platforms. Finally, escalation discipline ensures that each remote interaction results in a clear outcome, whether that is to continue, repeat the assessment the following day or escalate to in person care, so that "watchful waiting" remains intentional and properly documented [3, 4].

Barriers are likewise recurrent, regardless of setting or performance level. Cross border travel introduces licensure constraints when clinicians are not authorised in the athlete's temporary location. Connectivity is uneven in many training environments, which limits the reliability of video assessments and data uploads. Expectations about data ownership vary between athletes, clubs and vendors, creating confusion unless they are addressed explicitly at programme launch. Teams that clarify these issues up front, including consent boundaries, licensing coverage for planned travel routes and offline contingencies, report fewer disruptions and faster uptake among coaches and athletes [3, 4, 29, 30].

Telemedicine in athlete care comprises complementary models that differ by synchronicity, covering real time and asynchronous delivery; by clinical purpose, spanning triage, diagnostic support and longitudinal management; and by operational or legal requirements, which include licensing, consent, documentation, billing, and privacy and security. Implemented within a single, coherent pathway, these models reinforce one another: real time consultations address acute needs; asynchronous reviews streamline multidisciplinary input; and remote physiological monitoring (RPM) adds longitudinal context to decision making. Well structured programmes codify transitions and define clear triggers for in person examination whenever remote evaluation reaches its limits [1, 3, 4].

5.2. TELEREHABILITATION: EFFECTIVENESS AND PATIENT EXPERIENCE

Beyond non-inferiority on clinical outcomes, telerehabilitation succeeds when it preserves 'rehab momentum' short feedback loops, visible progress, and rapid re-booking after flares. In practice this means scheduling cadence for example weekly remote check-ins plus milestone in-person sessions, making exercise adherence visible to both athlete and therapist, and capturing short video clips to review technique asynchronously. Such micro-interactions build self-efficacy and protect adherence during travel or tournament windows. [5,7]

Equity and access matter as much as protocols. Programmes offer low bandwidth fallbacks, for example audio first coaching accompanied by still images, provide multilingual instructions, and use simple checklists for home safety and equipment. Where device loans are feasible, they reduce drop out in amateur settings. Where loans are not feasible, protocols explicitly support no device alternatives, including symptom scores and time based progressions [4].

From the therapist standpoint, high fidelity remote assessment depends on camera placement, lighting, and movement cues that standardise what is observable. A brief pre visit message with concrete examples-covering sagittal and frontal framing, an appropriate step back distance, and stable support-prevents poor quality sessions and reduces repeat visits caused by missing information [5, 7].

Across selected musculoskeletal indications, structured telerehabilitation programmes can match outcomes achieved during on-site therapy, provided that protocols and supervision are clearly defined. Experience improves with co-designed goals, visible progress, alternation of supervised/autonomous blocks, and rapid re-booking for flares. Post-pandemic cohorts favor hybrid care. Satisfaction correlates with clarity of progression and responsiveness of the team [5, 7].

5.3 REMOTE MONITORING DOMAINS AND DIAGNOSTIC POTENTIAL

The diagnostic potential of remote monitoring technologies varies depending on the type of data collected and the clinical context in which it is used. Table 2 outlines major remote monitoring modalities, their primary clinical applications, associated limitations, and potential sources of diagnostic error.

Table 2. Diagnostic potential and limitations of remote monitoring technologies in sports medicine

Technology	Parameter measured	Clinical application	Limitations	Risk of errors	Level of evidence	References
HRV	Autonomic regulation, recovery status	Load adjustment, monitoring of fatigue and recovery	High variability, dependence on measurement protocol	Misinterpretation of short term fluctuations	Moderate	[10–12]
GNSS / IMU	External load, movement patterns	Workload monitoring, detection of asymmetries	Reduced accuracy indoors, sensor drift	Incorrect load estimation, missed asymmetries	Moderate	[8–9, 13]
Sleep monitoring	Sleep duration, fragmentation	Recovery assessment, fatigue management	Limited accuracy of sleep stages	Overinterpretation of single night changes	Low to moderate	[14–15]
Continuous glucose monitoring	Interstitial glucose levels	Nutritional individualisation	Physiological lag, device dependent accuracy	Misleading interpretation during high intensity exercise	Low	[16–17]
Sweat sensors	Electrolytes, lactate, biomarkers	Hydration and metabolic monitoring	Calibration issues, environmental influence	False confidence in measurements	Low	[18]

ECG / PPG	Heart rate, rhythm	Screening, detection of arrhythmias	Signal artefacts, consumer device limitations	False positives or missed abnormalities	Moderate	[19]

5.3.1 Cardiovascular monitoring (HR, HRV, ECG/PPG): from screening to red-flag triage

Remote cardiovascular monitoring supports several routine decisions in athlete care. Day to day readiness can be tailored using HRV indices such as RMSSD and its weekly variability, while surveillance for overreaching and post illness recovery benefits from trend based interpretation rather than single day values. When athletes report palpitations or syncope, consumer grade signals prompt expedited review and, where indicated, medical grade ECG for red flag screening. Protocol discipline matters: posture, breathing cadence, caffeine intake and timing remain controlled so that derived metrics are comparable within the athlete across weeks. Reporting emphasises weekly means and within athlete variance and integrates sleep and subjective recovery to reduce false reassurance or over reaction [8–11].

5.3.2 Biomechanics and workload (IMUs, GNSS, EMG): external load, asymmetries, and movement quality

GNSS and IMUs quantify external load with metrics such as acute to chronic exposure, accelerations and decelerations, and jump counts or heights, while asymmetry indices highlight limb to limb differences that may warrant targeted retraining. Video assisted heuristics combined with IMU data can flag landing mechanics, trunk lean, or foot strike patterns for further evaluation, with referral to a gait laboratory when deviations persist. Practically, indoor environments and multipath artefacts degrade GNSS accuracy, so programmes rely on drift correction and magnetometer calibration as routine maintenance. Thresholds remain sport specific and are interpreted in the context of injury history and session intent [12].

5.3.3 SLEEP AND RECOVERY: MEASUREMENT REALISM AND DECISION RULES

Consumer wearables estimate sleep with variable accuracy at the stage level. Accordingly, decision rules prioritise macro trends,total sleep duration and wake after sleep onset, together with clinical symptoms rather than exact percentages per stage. During travel or jet lag, liberal thresholds for delaying training starts, combined with strategic light exposure and ‘sleep banking’, help stabilise readiness. In routine weeks, combining sleep trends with HRV and mood scores provides a more reliable view of accumulating stress than any single metric alone [13, 14].

5.3.4 BIOCHEMICAL SENSING AND HYDRATION (SWEAT, SALIVA): CURRENT PROMISE AND GAPS

Real time sweat sensors for electrolytes, lactate, and cortisol offer a path to personalised hydration and stress monitoring in the field, but translation from laboratory to training venues requires calibration against reference assays and explicit handling of artefacts such as motion, skin temperature, and variable sweat rates by environment. Protocols define sampling windows, environmental annotations, and decision thresholds, for example, triggers for electrolyte replacement to avoid ad hoc interpretation. Until device calibration drift and field variability are better characterised, clubs treat outputs as supportive context rather than stand alone decision makers [15, 16].

5.3.5 CONTINUOUS GLUCOSE MONITORING (CGM): GUIDANCE FOR NON DIABETIC ATHLETES

In non diabetic athletes, CGM proves most useful for structured fuelling experiments rather than performance prediction. Interpretation accounts for physiological lag between interstitial and blood glucose often up to 10–15 minutes together with catecholamine related elevations during high intensity work and device specific accuracy that depends on adhesive integrity and movement. Practical applications include testing carbohydrate timing in long sessions and identifying prolonged nocturnal hypoglycaemia risk after taxing workloads. By contrast, single session spikes or dips are read cautiously and in context with nutrition logs and perceived effort. Present evidence for performance enhancement remains inconclusive, so CGM complements rather than replaces established nutrition planning [16–19].

5.3.6 CONCUSSION ASSESSMENT AND FOLLOW UP: STRUCTURED REMOTE EXAM AND STAGED PROGRESSION

Core elements of a remote concussion assessment include an orthostatic screen, cranial nerve checks, oculo vestibular testing and a cervical evaluation, all of which adapt well to video with caregiver assistance and clear instructions. Sideline teleconsultations standardise immediate decisions where specialist presence is limited. However, any red flag mandates removal from play and prompt in person evaluation. Return to play proceeds through symptom limited activity, light aerobic work, moderate training, heavy non contact participation, full contact practice and competition, with at least twenty four hours between stages and an automatic step down if symptoms recur [20–22].

5.3.7 FEMALE ATHLETE HEALTH AND SPECIAL POPULATIONS: TAILORING PROTOCOLS

Cycle aware tracking helps contextualise HRV and sleep variation. Rigid thresholds that ignore hormonal modulation are avoided. During pregnancy and the peripartum period, symptom led progressions, pelvic floor safe exercises, and return to sport decisions anchored in discomfort and functional tests protect safety. For youth, short, simple captures with high touch education improve adherence, while for para athletes, sensor placement may require adaptation to residual limbs or trunk with an expectation of higher artefact rates and a need to corroborate signals with clinician observation [13, 14].

5.3.8 MULTIDISCIPLINARY WORKFLOWS AND DATA OPERATIONS: FROM INTAKE TO ESCALATION

Practical operations assign roles across physicians, physiotherapists, strength and conditioning staff, nutrition, psychology, and data leads, and then standardise data ingestion naming, time stamps, and units together with quality thresholds for missingness and artefacts. Metadata such as session type and environment are recorded consistently, while escalation categories (clinical, performance, technical) include clear turnaround targets. Access follows least privilege principles, and all views and exports are logged. Teams periodically review access lists and remove dormant accounts to limit unnecessary exposure [1, 3, 30].

5.3.9 Sport specific considerations: endurance, team, and contact sports

In endurance contexts, HRV trend interpretation pairs with subjective fatigue and iron status, and CGM based fuelling experiments run under controlled conditions to avoid over interpreting transient fluctuations [9, 16]. In team sports, monitoring focuses on accelerations, high speed running, and asymmetries, while automated prompts for concussion screening are embedded within routine workflows [12, 10]. In contact and combat sports, tele triage scripts and neurological red flag checklists are prepared for travel events, with explicit coordination with event medical leads to enable rapid evacuation if needed [20–22].

5.4 ARTIFICIAL INTELLIGENCE AND PREDICTIVE ANALYTICS

Reporting standards help translate modelling into safe clinical support. Recent guidance consolidates requirements for prediction studies and trials. TRIPOD+AI recommends transparent reporting across model lineage, calibration and fairness, and includes a dedicated checklist for abstracts. SPIRIT AI and CONSORT AI specify protocol and trial report items for AI interventions, covering versioning, human–AI interaction, inputs and outputs, and error analyses. Applying these checklists when describing club level deployments improves reproducibility and reduces avoidable bias [40, 41].

Explanations must be practical: clinicians need concise, case level rationales rather than abstract model theory. In most team settings, a ranked list of top features for the individual prediction, a short rationale in plain language such as ‘three consecutive days of sleep fragmentation with rising load’, and a pointer to counterfactuals describing what would lower the estimated risk are sufficient. More complex explanations or global plots can be placed in a background ‘learn more’ panel to avoid cognitive overload during clinics or sideline triage [23, 24].

A controlled ‘shadow-mode’ run-in reduces implementation risk by testing calibration and action thresholds before alerts become operational. Agreement rates, calibration curves and decision-curve analyses are then reviewed against pre-set acceptance criteria before any flag becomes actionable. This approach reduces the chance that a model with decent discrimination but poor calibration will distort thresholds for escalation or RTP clearance. [23,24,25]

Accountability requires an audit trail: who viewed a prediction, what action followed, and whether outcomes improved. Teams should appoint a model steward to oversee drift monitoring and fairness checks (sex, age, sport). Periodic reports to governance bodies ensure that predictive analytics remain decision-support rather than de facto policy. [23,24,25]

Human factors drive safe use. Interfaces expose uncertainty bands and plain language explanations of what contributes most to a prediction. Short decision scripts for instance, reduce load and retest after 48 hours once risk crosses a threshold help standardise responses across clinicians. Training sessions include examples of false positives and false negatives and their operational cost [23, 24].

Data operations for modelling in clubs differ from academic pipelines. Event labels and workload features are versioned across seasons, with change logs that explain label revisions including updates to injury definitions and feature recalculations. Without this ‘data readiness’, discrimination metrics are misleading and deployment cannot be audited [23, 24, 25].

Finally, human in the loop arrangements formalise that clinicians retain authority while using predictions as decision support. Interfaces surface uncertainty, including prediction intervals, and present counterfactuals that state the expected change in risk if workload is reduced or recovery is extended. This aligns with recommendations to keep models interpretable at the point of care [23, 24, 25].

Model governance matters as much as performance. Teams register data lineage, feature provenance and access logs, and appoint a model steward responsible for drift monitoring and post deployment audits. Fairness checks across sex, age and sport categories are performed to avoid systematic under or over triage [23, 24].

In athlete contexts, the most common pitfalls include label drift (changing injury definitions across seasons), leakage from future information in rolling aggregates, and under reporting of calibration. Practical reporting includes class balance, temporal split diagrams and decision curve analyses to clarify net benefit at relevant thresholds [23, 24, 25].

For AI workflows, authors specify data lineage, feature definitions, time windows and leakage controls, use rolling origin evaluation to emulate deployment, and report calibration and decision curves rather than relying solely on AUC. Clinically, models support rather than replace judgement and they highlight uncertainties and counterfactuals, for instance the expected change in risk associated with a reduction of weekly load by fifteen percent.

Deployment includes monitoring for drift and fairness across sex, age and sport. Negative studies and external validations are published to reduce publication bias [23–25].

Linking analytics to day-to-day athlete care requires clear governance and privacy safeguards. The next section translates these modelling principles into operational, ethical, and legal practice for teams and federations. [44,45,48,51]

5.5 IMPLEMENTATION, PRIVACY AND ETHICS

Processing of athlete biometrics and health signals engages special-category protections. Under GDPR, health and biometric data require an Article 6 lawful basis and an Article 9 condition with appropriate safeguards. Regulators emphasise DPIA, purpose limitation and minimisation for biometric recognition workflows. Interface design should make withdrawal as straightforward as opt-in and record a verifiable audit trail. [44,51]

Privacy-by-design at product level complements policy controls. ISO 31700-1 outlines high-level requirements for embedding consumer privacy across the lifecycle of connected devices and services (roles and authorities, preference capture, HCI for privacy, breach preparedness). Applied to wearables, this maps to service-life documentation, explicit preference UIs, and deletion workflows upon device retirement. [50]

Cybersecurity expectations continue to rise in European health. ENISA reporting identifies ransomware and data breaches as leading threats for providers and recommends procurement and cloud practices that include logging, backup/restore, and supply-chain assurance. Tele-enabled teams should align their vendor selection and incident response with these sector recommendations. [48,49]

Role design prevents ‘scope creep’. A small governance triangle: care lead (team physician), data lead (responsible for ingestion, QA, dashboards), and athlete representative- meets on a fixed cadence to approve secondary uses, review incidents and access audits, and retire legacy data no longer needed for care. Minutes are summarized in plain language and shared with the squad. Where anti-doping systems operate in parallel (ABP/ADAMS), minutes should explicitly note that no routine care data crossed into compliance workflows. [1,29,30]

Withdrawal-as-easy-as-opt-in should be enforced at both policy and interface levels. Athletes need a clearly visible control to pause or revoke performance-layer processing without affecting access to clinical care. Requests must trigger a documented workflow: acknowledgment within a set period, role-scoped removal of access, and confirmation that downstream analytics no longer ingest the athlete’s streams. Publishing monthly counts of withdrawals and restorations improves accountability and sets expectations. [1,3,29]

Data councils with athlete representation can approve secondary uses, select vendors, define red-flag escalation and review incident post-mortems. Publishing a concise governance charter clarifies expectations for all stakeholders and accelerates recovery during incidents. [29,30]

Separation of streams by design safeguards trust: clinical records remain inaccessible to anti doping systems, while ABP and ADAMS data do not flow into routine care analytics. Role based access and technical partitioning, for example the use of separate tenants or distinct data lakes, help enforce policy [29, 30].

International travel adds jurisdictional complexity. Operational plans list the clinicians who are licensed in each region, the approved locations for data storage and processing, and the contingency arrangements for low bandwidth venues where connectivity is limited. Clear procedures for issuing and retrieving devices, together with explicit steps that describe how missing data are flagged, reduce loss and minimise data gaps [1, 3, 4].

Granular consent in practice relies on layered permissions. The core care layer provides minimum necessary access with retention aligned with medical record requirements. The optional performance layer covers analytical use for training decisions and depends on the athlete’s explicit opt in and ability to revoke participation. A distinct research and education layer governs secondary uses approved through independent review and aggregation. Withdrawal remains as visible and straightforward as the initial opt in [1, 3].

To build trust, athletes are represented in data councils that approve secondary uses, select vendors and define red flag escalation. Publishing governance charters and incident response playbooks reduces ambiguity and accelerates recovery when issues arise [29, 30].

Cross border competition adds complexity: medical licensure and data transfer rules vary by jurisdiction. Programmes document which clinician is licensed where and whether data are stored in region or under appropriate safeguards. Separation of clinical and anti doping streams is enforced both in policy and in system architecture [1, 3, 30].

Operational checklists include platform hardening through single sign on with multi factor authentication, encryption applied to stored data and data in transit, tamper evident logging and periodic access reviews. Consent materials provide plain language explanations of primary use related to clinical care, optional secondary use related to education or research, retention periods and the right to withdraw without penalty [1, 3, 4].

A practical approach to governance is to separate three decision layers. The care layer covers clinician–patient use, minimum necessary access and retention aligned with medical record requirements. The performance layer covers analytical use for training decisions and depends on an athlete's explicit opt in and clear revocation rights. The research and education layer governs secondary uses that undergo independent review and aggregation. Distinguishing these layers prevents scope creep and clarifies who may see particular data, at what time and for what purpose [1, 3, 29, 30].

Consent language enumerates data types such as vital signs, movement data, sleep measures and biochemical signals, together with their purposes in clinical care or in research and education, as well as retention terms, rights to withdraw and any sharing with team staff or external parties. Under GDPR, processing of biometric and health data requires explicit consent or another lawful basis, and minimum necessary access with strict purpose limitation remain core expectations. Debates on athlete data sovereignty support giving athletes a direct voice in governance bodies, for example through participation in data councils. Anti doping data from ABP and ADAMS programmes remain strictly separate from routine care analytics. Regular tabletop exercises for security incidents and practice runs of data deletion workflows reinforce preparedness and operational compliance [1, 3, 26–30].

With roles, consent layers, and safeguards defined, the framework below turns policy into practical steps that clinicians and performance staff can apply consistently across the season. [1,3,4]

5.6. A PRAGMATIC FRAMEWORK FOR CLINICIANS AND PERFORMANCE TEAMS

Interoperability. Teams prefer HL7® FHIR® resources and profiles wherever available so that appointments, observations and care plans move predictably between club systems and external providers. National action plans increasingly promote FHIR as the common application programming interface for health data exchange [42, 43].

Define the clinical question and success criteria. Each pathway states an explicit clinical question and links decisions to measurable outcomes such as function, time loss, pain and patient reported outcomes, ensuring that evaluation is based on observable change rather than impressionistic judgement [5, 10].

Harmonise monitoring protocols. Signal capture follows consistent rules: morning, supine HRV with controlled breathing; nightly, continuous sleep. Session-based GNSS and IMU for external load and CGM used for fuelling experiments with nutrition logs. Harmonisation improves trend reliability and enables interpretable cross-athlete comparisons [8–12].

Synthesis and confirmation. Remote signals are interpreted alongside symptoms and workload, and confirm outliers on ≥2 consecutive days before action to limit false positives and unnecessary load changes [9, 13].

Adopt hybrid pathways. Combine tele-touchpoints onboarding, mid-block reviews, pre-RTP sign-off with targeted in-person testing at milestones to maintain momentum and preserve safety at decision gates [5, 7].

Governance essentials. Programmes document consent, enforce least-privilege and role-scoped access, maintain audit logs, test incident-response plans, and clarify hand-offs between clinicians and performance staff so that accountability remains visible through the season [1, 3, 4].

Evaluate impact. Review results across clinical dimensions such as fewer flare ups and safer return to play timing, across operational dimensions such as reduced travel, and across equity dimensions such as improved access for remote athletes, so that scaling decisions reflect real world benefit rather than technology availability alone [1, 4].

5.7 FUTURE DIRECTIONS

Accessibility and inclusion. Accessibility receives structured evaluation. WHO and ITU toolkits offer practical steps for inclusive telehealth language, disability support, bandwidth constraints adaptable to sport environments and testable in pragmatic trials [52].

Validation and impact beyond accuracy. Future studies prioritise sport and device specific external validation with predefined targets, such as a calibration slope close to 1.0 and narrow Bland–Altman limits of agreement, and run

prospective impact designs that demonstrate clinical or operational benefit rather than reporting AUC alone [23–25].

Interoperability trials. Because fragmented data flows remain a critical barrier, pragmatic trials evaluate FHIR based exchange across clinics, teams and vendor platforms, with measurable reductions in manual data work and fewer safety critical gaps, including missed alerts [1, 4].

Privacy preserving analytics at scale. Multi club consortia test federated learning or secure enclaves to enable model training without centralised raw data transfer, paired with governance Implementation science and equity. Adoption, fidelity and sustainability of tele enabled pathways are quantified across settings, including elite and amateur as well as urban and remote environments, using equity indicators and cost effectiveness endpoints such as time saved, avoided travel, unscheduled visits and time to RTP [1, 4].

Under-represented populations. Dedicated protocols and defined validation windows target youth, female athletes across different life stages and para athletes. Studies set sex specific thresholds, specify sensor placement and describe artefact handling procedures to minimise biased conclusions [13, 14].

Multimodal fusion. Head to head comparisons of multimodal strategies, for example combining HRV, sleep measures and GNSS derived workload, with single modality approaches use pre specified rules that remain simple enough for field use yet robust to noise and non adherence [8–13].

Anti-doping intersections. Programmes formalise the separation of care related data and compliance related data such as information from ABP, whereabouts systems and CGM derived signals. They audit access control and embed athlete representation in data governance councils to safeguard trust and prevent scope creep [29, 30].

5.8 CURRENT EVIDENCE AND PRACTICE: KEY LIMITATIONS

Heterogeneity of devices and protocols limits generalizability. HRV capture varies by sensor type ECG vs. chest-strap vs. wrist PPG, posture, breathing cadence, and timing; many studies use small, homogeneous samples and short horizons, which inflates apparent stability and effect sizes [8–11].

Device validity is sport, context, and placement-dependent. GNSS accuracy degrades indoors and in dense urban canyons. IMU drift and magnetometer issues persist without frequent calibration. Many field studies lack criterion standards or report partial metrics only [12].

Sleep metrics from consumer wearables are useful for trends but imprecise at the stage level. Decisions based on single-night changes risk over-reaction. Harmonized analytics and transparent algorithms are not yet standard across vendors [13,14].

Biochemical wearables like sweat or saliva show promise but face calibration drift, environment-dependent sweat rates, motion and temperature artifacts. Real-world thresholds for actionable decisions remain to be validated beyond lab settings [15,16].

CGM in non-diabetic athletes is feasible for fueling personalization, but evidence for performance enhancement is inconclusive. Physiological lag and intensity-related artifacts complicate interpretation during high-intensity efforts [16–19].

Tele-concussion workflows are feasible for follow-up and sideline decision support, yet evidence for baseline and sideline tele-testing remains limited. Red-flag escalation must dominate convenience in travel or tournament settings [20–22].

AI models often report promising discrimination without robust external validation, calibration, or decision-curve analysis; small datasets, shifting injury definitions and absence of impact trials hinder clinical translation and safe deployment [23–25].

Governance and compliance constraints persist: cross-border licensing, GDPR obligations for biometric and special-category data, vendor contracts, and cybersecurity. Separation of clinical care data from anti-doping systems is essential but not uniformly enforced [1,3,26–30].

Operationally, many programmes underestimate the workload associated with data operations, including ingestion, quality assurance and metadata standards, as well as user training and change management. Without clear escalation rules and appropriate education, remote physiological monitoring increases noise and contributes to alert fatigue [1, 3, 4].

Priorities include prospective and sport specific validation of RPM biomarkers against clinical outcomes, multimodal fusion supported by transparent and monitored artificial intelligence, interoperability based on FHIR standards, privacy preserving analytical approaches, implementation science and cost effectiveness assessment, inclusion of youth, female athletes and para athletes, sustainability of device lifecycles and rigorous evaluation of tele enabled return to play pathways [13, 14].

Effective clinical use of remote data requires structured approaches to interpretation and integration into decision-making processes. Table 3 presents common interpretative strategies, typical errors, and principles supporting safer clinical use of remote monitoring data in sports medicine.

Table 3. Interpretation of remote data and clinical decision making in sports medicine

Approach to interpretation	Data used	Clinical application	Typical errors	Clinical consequences	Principles of safe use	References
Single parameter assessment	HRV, HR, CGM, sleep	Rapid screening, initial orientation	Overinterpretation of isolated values	Incorrect load adjustment, unnecessary restrictions	Avoid isolated decisions, require contextualisation	[10–12, 16]
Trend analysis	HRV trends, workload, sleep	Monitoring recovery and adaptation	Ignoring external factors and context	Accumulation of overload, delayed detection of fatigue	Use multi day data with clinical correlation	[11–14]
Multimodal integration	HRV, GNSS, sleep, symptoms	Comprehensive assessment of athlete status	Inconsistent data integration, conflicting indicators	Misclassification of risk, inappropriate clinical decisions	Combine objective and subjective data	[8–12, 14]
Algorithm based assessment	AI models, predictive analytics	Risk stratification, decision support	Bias, lack of external validation	Underestimation or overestimation of injury risk	Use only as supportive tool, require clinical oversight	[20–22]
Patient reported integration	PROs, symptom diaries	Monitoring symptoms and rehabilitation progress	Reporting bias, low adherence	Missed deterioration, delayed intervention	Validate data with objective measures	[1, 3, 4]
Hybrid clinical model	Combined remote and in person data	Return to play decisions, complex cases	Overreliance on remote data	Premature return, increased re injury risk	Mandatory in person verification in critical decisions	[5–7, 32]

5.9 A NARRATIVE RTP DECISION FRAMEWORK INFORMED BY TELE-DATA

Core decision pillars. Clearance decisions for return-to-play (RTP) integrate four complementary pillars. First, clinicians verify resolution of symptoms and stability of clinical signs obtained through targeted examination. Second, functional testing aligned with the demands of the athlete's sport confirms that task-specific movements can be performed without pain provocation or compensations. Third, monitoring stability is demonstrated across 7–14 days, with convergent trends in HRV, sleep and workload rather than isolated daily values. Fourth, the contextual layer competition calendar, travel and scheduling constraints frames residual risk and operational feasibility for graded re-entry [10–12, 32–34].

Staged progression and gates. RTP proceeds through a structured sequence of activity: symptom-limited exercise, light aerobic work, moderate training, heavy non-contact participation, full-contact practice and, finally, competitive play. Each gate requires the absence of symptom exacerbation during and after the session and a minimum twenty-four-hour interval before advancing. Any recurrence of symptoms triggers a step-down to the previously tolerated stage, with re-evaluation of functional and contextual factors before re-attempting progression [10–12, 32–34].

Role of tele-enabled monitoring. Tele-generated signals inform rather than replace clinical judgement. HRV is reviewed as a trend in parallel with sleep continuity and fragmentation and objective workload exposure for example session-RPE with GNSS/IMU features, and discrepancies between subjective recovery and biometrics prompt targeted clinical review. Programmes prioritise multi-day stability over single-day fluctuations to avoid reactive decisions based on noisy data. When trends appear stable and functional testing aligns with sport-specific demands, the physician confirms progression to the next gate [10–12, 32–34].

Shared decision-making and documentation. The team physician retains clearance authority and records the rationale for each transition, citing symptom behaviour, functional performance and monitoring stability. Athletes receive clear expectations for self-monitoring and red-flag escalation, and coaches align session content with the current gate to prevent premature load spikes. This narrative approach links clinical reasoning with measurable data, which supports transparency during hand-offs and post-event review [10–12, 32–34].

Operational safeguards. Tele enabled RTP pathways embed three safeguards. First, they apply pre defined stop rules, including pain resurgence, vertigo and disproportionate fatigue. Second, they require time stamped notes that mirror the structure of in person records. Third, they specify explicit next actions, whether to continue, repeat the activity the following day or escalate to in person care, and these actions are applied after every checkpoint. Where travel or congestion of fixtures is present, teams schedule brief remote check ins to verify tolerance and book targeted in person assessments at milestones [10–12, 32–34].

5.10 ECONOMICS AND SUSTAINABILITY CONSIDERATIONS

Environmental sustainability benefits from minimum service-life requirements, repairability, and vendor take-back schemes for batteries and devices. Choosing platforms that allow data export and vendor portability mitigates lock-in and future migration costs. [1,38]

A pragmatic value framework contrasts avoided travel and unplanned visits with costs and observed outcomes, such as fewer flare ups and shorter time to return to play, while time bounded pilots with preregistered metrics and clear scale down criteria prevent indefinite continuation of low value deployments [1, 4].

Total cost of adoption spans device procurement and replacement cycles, adhesives and other consumables, platform licensing, connectivity, training time and the workload of data operations across ingestion, quality assurance and dashboarding. Budgets account for sensor loss, battery replacement and translation for multilingual squads [1, 4].

Sustainability extends beyond finance: device durability, repairability, and recycling plans reduce environmental footprint. Procurement can specify minimum service life and vendor take-back schemes; software choices that permit data export and vendor portability avoid lock-in and future migration costs. [1,38]

A simple value framework weighs avoided travel and unplanned visits against programme costs and measured outcomes such as faster return-to-play or fewer flare-ups. Where possible, teams should run time-bounded pilots with pre-registered metrics and a plan for scale-down if benefits do not materialize. [1,4]

Cost considerations are multi-layered: device procurement and replacement cycles, adhesives and disposables, platform licensing, training time, and data-operations workload (ingestion, QA, dashboarding). Budget lines should account for sensor loss and battery replacement, and for translation services in multilingual squads. [1,4]

Telemedicine can reduce travel and time costs and reallocate scarce specialist capacity. Remote physiological monitoring may reduce avoidable exacerbations and unplanned visits when escalation rules are defined. Programmes budget for the device lifecycle, including replacement, calibration and consumables, along with data platform costs and staff training. Sustainability planning includes battery replacement and recycling, and procurement that favours repairability and a longer service life [1, 4].

In practice, realizing these efficiencies depends on disciplined escalation rules, transparent documentation of when remote data change decisions, and routine quality checks on device adherence and signal integrity. Programmes that pre-register operational metrics such as avoided unplanned visits, time-to-RTP, and athlete-reported usability are more likely to identify where tele-enabled pathways add value and where they should be scaled back. Periodic reviews of access logs and consent status further strengthen trust and reduce downstream incidents without adding excessive administrative burden. [1,4,38]

Taken together, these economic and operational considerations highlight the need for clear, role-specific guidance on how telemedicine and RPM should be applied in practice. The following conclusions distill practical, role-specific guidance for researchers, organisations, and clinicians. [1,3,4]

6. DISCUSSION

The results obtained correspond to the stated aim of the review and allow a structured assessment of the clinical applicability, limitations, and conditions for integrating telemedicine and remote monitoring in sports medicine. In contrast to most previously published studies, in which telemedicine, wearable devices, and organizational aspects are analyzed separately, this review integrates these components within a single clinical framework, with emphasis on decision points, conditions of data interpretation, and factors determining clinical reliability [1, 3, 4, 5–7, 38]. This approach allows a shift from a descriptive overview of technologies to an analysis of their actual role within the clinical workflow.

With regard to the first objective, telemedicine and remote monitoring are shown to be applicable in key clinical scenarios, including injury assessment, rehabilitation monitoring, and return to play decision making [5–7, 20–22, 32–34]. Unlike descriptive reviews limited to listing areas of application, these scenarios are presented as interconnected stages of a unified process. The reliability of remote assessment depends on standardized video consultations, the use of structured protocols, and the incorporation of trend based analysis [1, 3, 4, 5–7]. Confirmation of deviations over several consecutive days is considered a practical tool to improve reliability, although such approaches do not represent universal clinical thresholds and must be interpreted within a specific clinical context [1, 3, 4, 5–7].

The second objective, addressing the diagnostic potential and limitations of wearable devices, is examined through comparison of different data types in relation to their clinical applicability. In contrast to studies focusing primarily on technical performance, this review demonstrates that the value of such devices is determined not by measurement accuracy alone but by the possibility of clinical interpretation [8–14]. Continuous glucose monitoring outside diabetes remains a tool for nutritional individualization rather than performance assessment, reflecting a gap between data availability and clinical relevance [16–19]. Limitations include a physiological delay of 10–15 minutes and artifacts during high intensity activity [16–18]. Similarly, sweat sensors remain at a stage of limited clinical applicability due to calibration and environmental variability [15].

The third objective, concerning interpretation of remote data within the clinical process, shows that the key contribution lies in shifting the focus from isolated parameters to dynamic decision making models. Unlike approaches where data are considered independently, this analysis emphasizes their integration into clinical algorithms [5–7, 23–25]. The use of multi day observations and clinically justified thresholds improves interpretability, although such parameters should be regarded as practical models rather than standardized recommendations [11, 23–25]. In the field of artificial intelligence, existing approaches, including models suggesting load reduction as a risk mitigation strategy, remain hypothetical and require external validation and prospective confirmation in accordance with TRIPOD AI and CONSORT AI frameworks [23–25, 40, 41]. This clarifies the limits of applicability and contrasts with more optimistic interpretations reported in some publications.

The fourth objective, addressing organizational and regulatory factors, demonstrates that implementation depends not only on technological capacity but also on healthcare system structure. Unlike reviews that consider these aspects in isolation, this analysis integrates them into the clinical context. Interoperability, including the use of HL7 FHIR, and regulatory frameworks, including cross jurisdictional licensure, influence continuity of care and process management [1, 3, 4, 31, 42, 43]. These findings are consistent with existing literature and implementation reports from WHO and the World Bank, but extend them by linking organizational factors to clinical decision making [1, 37, 38].

The fifth objective, related to data protection and ethical considerations, is addressed not only as a regulatory requirement but as a determinant of system sustainability. In contrast to purely formal descriptions, this review connects privacy by design principles with practical implementation. Compliance with GDPR related frameworks, EDPB guidance, WADA standards, and ENISA cybersecurity recommendations, together with ISO and ICO guidance on biometric data, is identified as necessary to ensure trust and scalability [26–28, 44, 45, 48–51]. Accessibility considerations, including those outlined in WHO and ITU guidance, further determine equitable implementation [49].

The limitations of this review should be considered. The study is a narrative analysis and does not include formal assessment of study quality or risk of bias. The included sources are heterogeneous in design, populations, and technologies. Numerical parameters reported in the text, including observation intervals and load related indicators, do not represent universal clinical thresholds and reflect only approaches described in the literature. Data on emerging technologies, including biochemical sensors and artificial intelligence methods, remain limited and are largely lacking external validation and prospective confirmation [15, 23–25, 40, 41]. The inclusion of regulatory and methodological documents increases practical relevance but reduces the homogeneity of the evidence base.

Thus, the main contribution of this review lies in integrating previously fragmented research directions into a unified clinical model, in which telemedicine and remote monitoring are considered through the lens of decision making, data interpretation, and organizational conditions [1, 3, 4, 5–7, 38]. This approach allows a more precise delineation of the boundaries of applicability and defines the conditions for safe and evidence based use of these technologies in sports medicine.

7. CONCLUSIONS

Telemedicine and remote monitoring offer significant value in sports medicine for injury assessment and rehabilitation when integrated into structured clinical pathways. However, current evidence is heterogeneous, and remote formats carry risks such as underestimating injury severity or missing complications due to the lack of physical examination.

Wearable technologies, including continuous glucose monitoring and sweat sensors, often lack sufficient validation for performance optimization and can produce measurement artifacts. Relying too heavily on these devices may lead to inappropriate risk stratification. Similarly, while longitudinal data trends can assist decision-making, they are not yet standardized, and unvalidated AI models may introduce systematic errors in risk assessment.

Successful implementation depends on robust data governance, legal clarity, and managing conflicts of interest between medical safety and performance goals. Ethical concerns regarding data privacy also impact clinical effectiveness and athlete trust.

Ultimately, remote data should remain supportive rather than definitive. Future research must prioritize prospective studies on clinical outcomes like re-injury rates. In practice, mandatory clinical verification is essential for high-risk decisions, particularly return-to-play, to avoid diagnostic errors and prolonged recovery times.

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The authors declare no conflict of interest.

DECLARATION OF THE USE OF GENERATIVE AI

The authors used generative AI tools only for minor language editing and reference formatting. All content was created solely by the authors.

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