



FROM WEARABLES TO AI: A SYSTEMATIC REVIEW OF DIGITAL TECHNOLOGIES FOR INJURY PREVENTION AND MANAGEMENT IN TEAM SPORTS

OD NOSIVIH UREĐAJA DO UMJETNE INTELIGENCIJE: SISTEMSKI PREGLED DIGITALNIH TEHNOLOGIJA ZA PREVENCIJU I ZBRINJAVANJE OZLJEDA U TIMSKIM SPORTOVIMA

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ABSTRACT

Sports injuries pose significant risks to athletes, prompting the adoption of technologies for prevention, detection, and monitoring.

This systematic review aims to review the current landscape of digital tools in the prevention, detection, and monitoring of injuries in team sports. By analyzing recent studies, we will explore the impact of these technologies, identify potential limitations, and discuss future directions for research and application in sports medicine.

We conducted a systematic review following PRISMA guidelines (PROSPERO: CRD42024601280), searching PubMed, Scopus, and Web of Science (1969–2024) for studies including means of technology that can be assessed regarding the prevention, detection, and monitoring of injuries in team sports. The quality assessment of these references was carried out in accordance with the Joanna Briggs Institute Critical Appraisal Tools (JBI) guidelines.

Twenty-three studies were included. Fourteen studies focused on the assessment and detection of head Injuries and concussions, particularly in contact sports such as Australian football, rugby, and soccer. Musculoskeletal injuries represented the second type of injuries studied. Wearable technologies were the most frequently used technology for injury prevention, detection, and monitoring;

SAŽETAK

Sportske ozljede predstavljaju značajan rizik za sportaše što potiče i usvajanje tehnologija za prevenciju, otkrivanje i praćenje.

Ovaj sustavni rad ima za cilj dati pregled digitalnih alata koji se danas koriste u prevenciji, otkrivanju i praćenju ozljeda u timskim sportovima. Analizom pregledanih studija istražiti ćemo utjecaj tih tehnologija, identificirati potencijalna ograničenja i raspraviti buduće smjerove istraživanja i primjene u sportskoj medicini.

Proveli smo sustavni pregled slijedeći smjernice PRISMA (PROSPERO: CRD42024601280), pretražujući PubMed, Scopus i Web of Science (1969–2024) za studije koje uključuju tehnološka sredstva koja se mogu procijeniti u pogledu prevencije, otkrivanja i praćenja ozljeda u timskim sportovima. Procjena kvalitete ovih referenci provedena je u skladu sa smjericama Joanna Briggs Institute Critical Appraisal Tools (JBI).

Uključene su 23 studije. Četrnaest studija usmjereno je na procjenu i otkrivanje ozljeda glave i potresa mozga, posebno u kontaktnim sportovima poput australskog nogometa, ragbija i nogometa. Ozljede mišićno-koštanog sustava predstavljale su drugu vrstu proučavanih ozljeda.

Nosive tehnologije bile su najčešće korištena tehnologija za sprječavanje, otkrivanje i praćenje ozljeda, a nekoliko ih

several studies combined them with video analysis to enhance their accuracy. The integration of machine learning techniques was observed in two studies, particularly in soccer and rugby. Imaging technologies, such as shear-wave ultrasound elastography, were also used to assess posterior shoulder capsule stiffness in baseball pitchers.

Digital tools enhance injury management but require standardization. Future research should prioritize cost-effective solutions and clinician-AI collaboration.

Keywords: artificial intelligence, Internet of Things (IoT), wearable devices, team sport, sport medicine

INTRODUCTION

Throughout history, from ancient gladiatorial combat to modern Olympic competition, risk of injuries has been an inherent aspect of sports. Athletes, in their quest for peak performance, constantly navigate the delicate balance between pushing their limits and the potential for injury⁷. Sports injuries encompass a range of conditions, arising from contact, non-contact forces, or repetitive overuse². These injuries may impact different tissues, such as muscles, ligaments, and bones. Among these, stress fractures are especially common in sports, largely due to the repetitive motions inherent in many athletic activities²⁵.

In recent years, the advent of digital technologies has revolutionized the field of sports medicine, offering new avenues for injury prevention, detection, and monitoring. These innovations enable coaches and medical teams to gather real-time data, assess athletes' physical conditions, and identify potential injury risks before they manifest.

Injury prevention has been transformed by the introduction of wearables with Internet of Things (IoT) capabilities, such as gyroscopes and accelerometers, which allow for real-time biomechanical monitoring²⁵. Evidence-based integration is necessary since relying on these technologies without clinical validation increases the potential of misdiagnosis. These devices, which make use of micro-sensors like magnetometers, gyroscopes, and accelerometers, offer useful information that can be utilized to detect and reduce the risk of injuries and enhance the results of rehabilitation. In order to help with injury prevention and performance optimization, athletes' movement patterns may be analyzed using Inertial Measurement Units (IMUs), which measure motion-related metrics¹.

While these technologies have a lot of potential, relying too much on them could reduce the value of human judgment. They must be carefully applied, making sure they complement the organization's objectives and core beliefs, in order to optimize their advantages. This calls for a multifaceted strategy that takes into account the opinions

je studija kombiniralo s video analizom kako bi se poboljšala njihova točnost. Integracija tehnika strojnog učenja uočena je u dvije studije, posebno u nogometu i ragbiju. Slikovne tehnike, poput ultrazvučne elastografije posmičnim valom, također su korištene za procjenu posteriornog adhezivnog kapsulitisa ramena kod bacača u bejzbolu.

Digitalni alati poboljšavaju upravljanje ozljedama, ali zahtijevaju standardizaciju. Buduća istraživanja trebala bi dati prioritet isplativim rješenjima i suradnji kliničara i umjetne inteligencije.

Ključne riječi: umjetna inteligencija, internet stvari (Internet of Things – IoT), nosivi uređaji, ekipni sportovi, sportska medicina

of all stakeholders, analyzes current trends in technology adoption, and evaluates perceived impacts⁷. However, integrating technology into sports injury management presents challenges. Concerns remain about the consistency and precision of specific devices, emphasizing the necessity for thorough verification and validation processes.

This systematic review aims to review the current landscape of digital tools in the prevention, detection, and monitoring of injuries in team sports. By analyzing recent studies, we will explore the impact of these technologies, identify potential limitations, and discuss future directions for research and application in sports medicine.

1. METHODS

This is a systematic literature review conducted to determine the current landscape of digital tools in the prevention, detection, and monitoring of injuries in team sports. This study was carried out in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency and methodological rigor. The present study has been registered in the International Prospective Register of Systematic Reviews (PROSPERO), with the registration number CRD42024601280.

1.1. Research Strategy

We utilized a method based on the PICO format as follows:

P: Population

I: Intervention

C: Comparison

O: Outcomes

- Population: Athletes in team sports.
- Intervention: Digital tools (e.g., apps, wearable devices, software platforms).
- Comparison: No comparison groups.
- Outcome: Identification of digital tools that help directly or indirectly prevent, detect or monitor injuries in team sports.

Our research question was as follows: What are the various means of technology that can be assessed regarding the prevention, detection and monitoring of injuries in team sports?

The search query was defined using various combinations of keywords and Medical Subject Headings (MeSH) terms separated by Boolean operators. The search query was as follows: ((wearable OR “Internet of things” OR technology) AND (“Sports injury*” OR “Sports medicine”) AND (soccer OR football OR basketball OR rugby OR baseball OR handball OR volleyball)).

The bibliographic sources consulted for this review were obtained from recognized medical search engines, specifically: PubMed, Scopus, and Web of Science. These databases were selected for their rigor and extensive coverage of the medical field, allowing access to relevant articles and documents.

1.2. Study selection

- Inclusion Criteria:
 - Original articles/documents, published reports.
 - Articles/documents published from 1969 to 2024. Older studies may lack relevance for modern tech (e.g., IoT).
 - Articles/documents in all languages.
 - Articles/ documents including means of technology that can be assessed regarding the prevention, detection, and monitoring of injuries in team sports.
- Exclusion Criteria:
 - Literature review/meta-analysis/systematic review articles.
 - Articles that explore sports other than team sports.

After automatic removal of duplicates using Zotero, titles and abstracts were screened for relevance. Subsequently, the full texts of potentially eligible articles were retrieved and assessed in detail for final inclusion based on the predefined criteria.

1.3. Data Extraction

The following data were extracted from each included study: Study characteristics (authors, and year), type of technology, the role of technology (Detection: Identifying existing injuries, Monitoring: Continuous tracking and real-time feedback, Prevention: Interventions to avoid injuries), Type of injuries, Team sport, Main objective of the study and the key finding.

1.4. Quality assessment

The quality assessment of these references was carried out by NBM and HG, in accordance with the Joanna Briggs Institute Critical Appraisal Tools (JBI) guidelines to ensure research rigor and transparency. We used the JBI checklists

for each study type - Cohort, Quasi-Experimental, Cross-sectional studies - answering the questions they presented to assess quality and determine the risk of bias.

2. RESULTS

2.1. Study selection

The total number of records identified from PubMed, Scopus, and Web of Science databases was 732. After removing 70 duplicates, the remaining references were screened based on reading the title and abstract, which led us to exclude 481 records. The remaining 181 references were sought for retrieval, resulting in 21 reports that were not retrieved. Consequently, the number of references assessed for eligibility is 160, among which we have excluded 137 after reading the full text. In total, 23 studies were included out of 732, which explains the exclusion of 709 references (Fig. 1).

The PRISMA flowchart in Fig. 1 illustrates the whole process of this study selection.

Based on the 23 studies included, this systematic review identified two main areas: (1) the typology of injuries, (2) the technologies used for prevention, detection, and monitoring of injuries.

2.2. Type of injuries

As described in Table 1, 14 studies focused on the assessment and detection of head injuries and concussions, particularly in contact sports such as Australian football, rugby, and soccer. Musculoskeletal injuries represented the second type of injuries studied: three studies examined Anterior Cruciate Ligament (ACL) injuries, while four focused on shoulder and throwing injuries in baseball-related research. Lastly, two studies addressed overuse injuries and general injuries.

2.3. Technologies

Fig. 2 presents a chronological timeline (2015–2023) that illustrates the evolution of wearable and sensor-based technologies used in sports injury detection, prevention, and monitoring. The timeline demonstrates increasing sophistication and diversity in the types of technologies applied to specific injury types across various sports.

Wearable technologies were the most frequently used technology for injury prevention, detection, and monitoring across various sports.

- Real-time biofeedback system: Used for the prevention and monitoring of ACL injuries in volleyball.
- Wearable head impact sensors (X patch): Used for the detection and monitoring of head impacts and concussions in Australian Football and Rugby. They were also used to compare head impact forces across different age groups in Australian Football.

- Motion analysis in lab and field settings (Xsens Link): Used for the prevention of ACL injuries in soccer. Although the study involves a wearable system, the source emphasizes the context (lab and field).
- Wearable sensors (mouthguard sensor): Used for the detection of head impacts in American Football.
- In-ear sensors: Used for the detection and monitoring of head impacts in Youth Soccer.
- Inertial-based wearable technologies: Used for monitoring concussions across multiple sports.
- Pitch tracking sensor: Used for monitoring throwing injuries in Youth Baseball.
- Head Impact Telemetry System (HITS): A helmet-integrated system used for the detection of head impacts in American Football. A similar system was used in combination with a mouthguard (X2).
- IMUs: Used in combination with Artificial Intelligence (AI) for the detection of ACL injuries in Rugby.
- Motus THROW™ sleeve and sensor: Used for the detection of throwing injuries in Baseball

Several studies combined wearable sensors with video analysis to enhance the accuracy of head impact detection. Mouthguard sensors were validated against video analysis in American Football, revealing the superior reliability of video-based assessments. Similarly, the X Patch was

combined with video validation in rugby and soccer, reinforcing the need for video confirmation to ensure sensor accuracy.

The integration of machine learning techniques was observed in two studies, particularly in soccer and rugby. Global Positioning System (GPS) data combined with AI algorithms were used for injury forecasting in soccer, showing high predictive accuracy for overuse injuries. Similarly, IMU-based AI systems have been applied in rugby to detect ACL injury-related gait patterns, thereby improving early injury detection.

Finally, imaging technologies were incorporated in one study, where shear-wave ultrasound elastography was used to assess the stiffness of the posterior shoulder capsule in baseball pitchers, providing valuable insights into tissue adaptations and potential injury risks.

2.4. Quality assessment

We used the JBI checklist for cohort studies for 19 references, the JBI checklist for Quasi-Experimental studies for four references, and the JBI checklist for Cross-sectional studies for one reference. All 23 included studies replied to most of the quality assessment criteria, which led us to conclude that the total of included references has a low risk of bias.

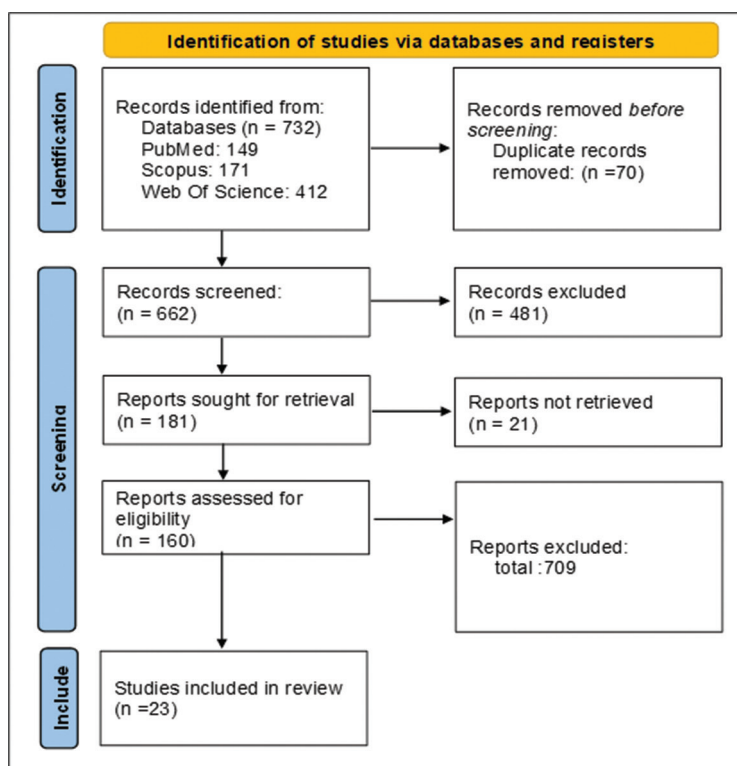


Figure 1 PRISMA Flowchart of Study Selection

Slika 1. PRISMA dijagram tjeka odabira istraživanja

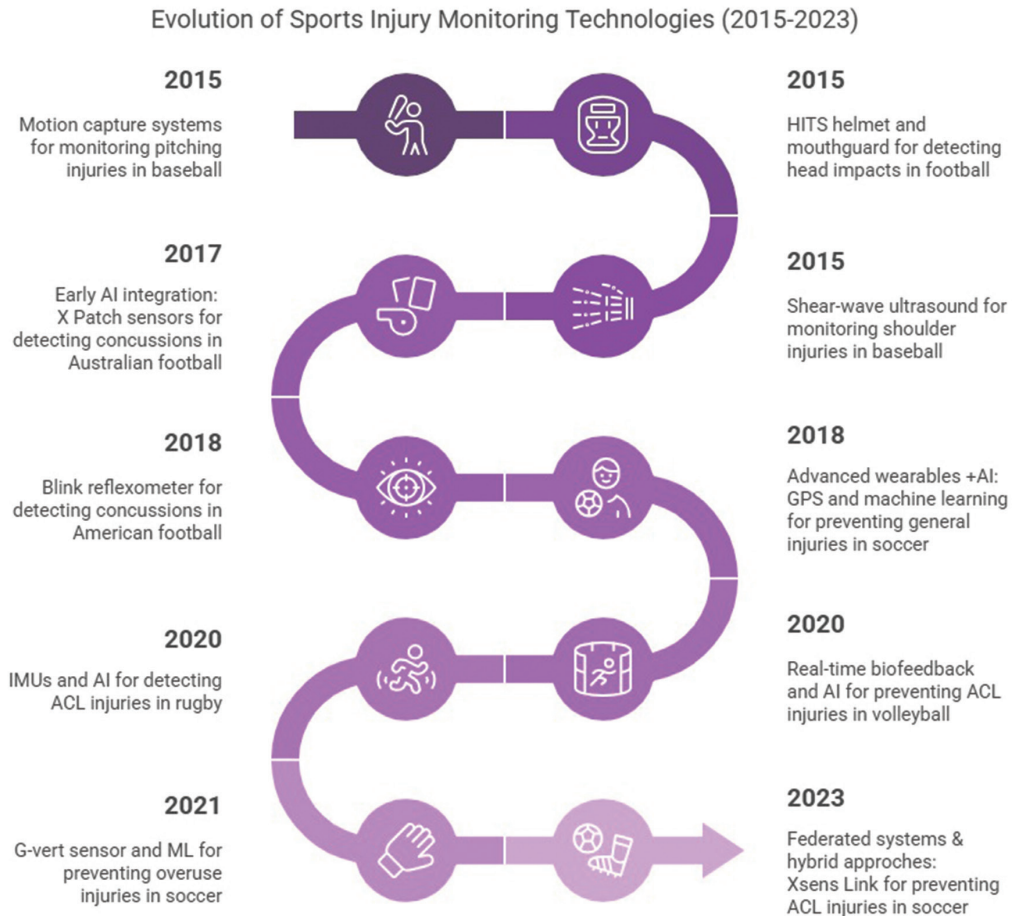


Figure 2. Evolution of sport injuries prevention, detection, and monitoring technologies
 Slika 2. Evolucija tehnologija za prevenciju, detekciju i praćenje sportskih ozljeda

Table 1. Synthesis of results from studies included in the systematic review
 Tablica 1. Sinteza rezultata studija uključenih u sustavni pregled

Author, date	Technology	Role	Type of Injury	Team sport	Main objective	Key findings
Bonnette et al. 2020 ³	Real-time biofeedback system	Prevention, monitoring	ACL injury	Volleyball	Develop a system to optimize motor learning and correct movement deficits	The system improved motor learning and movement efficiency
McIntosh et al. 2019 ¹⁶	Wearable head impact sensors (X patch)	Detection, monitoring	Head impacts, concussions	Australian Football	Assess the utility of wearable head impact sensors	Sensors provided useful impact data, but limitations in accuracy remain
Garner et al. 2018 ¹¹	Blink reflexometer device	Detection	Head impacts, concussions	American Football	Assess blink reflex as a concussion marker	Blink reflex parameters can objectively assess concussions and recovery
Pei-Hsi Chou et al. 2015 ²⁰	Motion capture systems	Monitoring	pitching-related injuries	Baseball	Analyze pitching biomechanics in late innings	Significant biomechanical changes occur in late inning, increasing injury risk
Di Paolo et al. 2023 ⁸	Motion analysis in lab and field settings (Xsens Link)	Prevention	ACL injuries	Soccer	Compare lab and field agility kinematics	Field agility tests better replicate injury mechanisms

Kuo et al. 2018 ¹⁵	Wearable sensors (mouthguard sensor) and video analysis	Detection	Head impacts	American Football	Compare accuracy of different impact assessment methods	Video-based systems more reliable than sensors alone
Rossi et al. 2018 ²⁶	GPS data and machine learning	Prevention, monitoring	General injuries	Soccer	Forecast injuries using GPS and machine learning	High accuracy in predicting injuries
Hecimovich et al. 2022 ¹⁴	King-Devick test with integrated eye tracking	Detection	Concussions	Rugby	Assesses the utility of the King-Devick test with eye tracking as a diagnostic tool for sport-related concussion	Suggests the integrated test is effective for diagnosing concussions
Sandmo et al. 2019 ²⁷	In-ear sensors	Detection, monitoring	Head impacts	Youth Soccer	Evaluates the effectiveness of in-ear sensors in quantifying head impacts	Indicates in-ear sensors can accurately measure head impact, but need a secondary means of verification
Powell et al. 2022 ²²	Inertial-based wearable technologies	Monitoring	Concussions	Rugby	Explores wearable technologies for objective monitoring in sports-related concussion	Highlights the potential of wearable technologies for monitoring concussion recovery
Freehill et al. 2023 ¹⁰	Pitch tracking sensor	Monitoring	Throwing injuries	Youth Baseball	Evaluates the feasibility of using a single sensor to quantify workload in youth baseball players	Finds that single sensor can effectively monitor pitch and throw counts, aiding in workload management
Campbell et al. 2020 ⁴	HITS	Detection	Head impacts	American Football	Assesses the accuracy of HITS in detecting and locating head impacts	Indicates that HITS provides reliable data on head impact detection and location
Siegmund et al. 2015 ²⁸	HITS and a mouthguard system (X2).	Detection, monitoring	Head injuries	Football	Validate sensor systems for head impact measurement	Both systems could effectively measure head impact severity, providing a reliable tool for assessing head impacts in football players.
Tedesco et al. 2020 ¹⁸	IMU and AI	Detection	ACL injuries	Rugby	Identify ACL gait patterns in rugby players in a real-world setting	Demonstrated that it is possible to discriminate between healthy and post-ACL injury subjects correctly
De Leeuw, 2021 ²¹	G-vert sensor and machine learning	Prevention, monitoring	Overuse injuries	Soccer	forecast injuries in soccer players using GPS and machine learning	The model could effectively predict injuries, suggesting that GPS data combined with machine learning can be used for injury forecasting in soccer
Takenaga et al. 2015 ²⁹	Shear-wave ultrasound elastography	Monitoring	Shoulder injuries	Baseball	Assess posterior shoulder capsule stiffness	Throwing shoulders had stiffer capsules

Mehta et al. 2019 ²³	Motus THROW™ sleeve and sensor	Detection	Throwing injuries	Baseball	Assess workload-injury relationship	Higher workload is associated with increased risk of throwing-related injuries in varsity baseball players.
Willmott et al. 2017 ³⁰	Wearable head impact sensors (X Patch)	Detection	Concussion	Australian Football	Assess Sport Concussion Assessment Tool, 3 rd edition (SCAT3) changes and head acceleration	Increase in symptom severity post game was not associated with X patch measured head acceleration events
Reyes et al. 2020 ²⁴	Wearable head impact sensors (X Patch)	Detection	Concussion	Australian Football	Evaluate head acceleration as a concussion screening tool	Use of X-Patch was not sufficiently reliable for identifying players for further concussion screening
Carey et al. 2019 ⁵	X Patch + video analysis	Detection	Head impacts	Rugby	Validate head impact sensor data using video	video verification was necessary for accuracy.
Carey et al. 2021 ⁶	X Patch + video analysis	Detection	Head impacts	Rugby	Verify sensor accuracy for direct head impacts	Video validation improved sensor reliability
Patton et al. 2020 ¹⁹	X patch + video analysis	Detection	Head impacts	Soccer	Confirm head sensor data with video	Video validation necessary for sensor accuracy
Hecimovitch et al. 2018 ¹³	Wearable head impact sensors (X patch)	Monitoring	Head impacts	Australian Football	Compare impact forces across age groups	Youth footballers experience similar head impact forces as junior and senior players

3. DISCUSSION

This systematic review studies the role of digital tools in terms of prevention, detection and monitoring of team sports injuries. Understanding the implications of technologies in sports injuries represents a solid support for further advancements to increase the accuracy of these methods.

Regarding injuries detection, devices like the X-Patch and in-ear sensors have shown success in detecting concussions and head injuries. Various studies^{5,16,30}, have confirmed the effectiveness of these devices by correlating their findings with video reviews and established assessment tools like SCAT3. These technologies not only aid in spotting clear concussions but also in detecting sub concussive impacts, which are typically more challenging to observe through conventional techniques⁶. Employing video validation in conjunction with impact sensors bolsters the accuracy of concussion identification, making it an invaluable resource for immediate clinical decision processes.

The area of injury prevention is a vital focus where advancements in technology are occurring rapidly. A prime illustration is the real-time visual biofeedback system created by Bonnette and colleagues³, which aids in enhancing motor learning and correcting movement

deficiencies that may result in injuries like ACL ruptures. This technology permits athletes to modify their movements instantly by utilizing visual feedback, which greatly diminishes the chances of biomechanical mistakes that could lead to injuries³. By incorporating such feedback mechanisms into athletic training, individuals can refine their movement techniques to safeguard delicate joints and tissues, ultimately helping to prevent injuries over time.

Additionally, AI and machine learning-driven predictive models have emerged as effective tools for injury prevention tailored to individuals. Rossi et al deployed AI algorithms to forecast injuries based on information gathered from GPS devices and various wearables²⁶. These predictive frameworks assist in dynamically tweaking training regimens, ensuring that athletes remain within safe limits that prevent overuse injuries. The strength of AI in this scenario lies in its skill to process extensive data sets and uncover trends that may elude human experts, enhancing injury prevention efforts to be more individualized and data-centric. This method enables real-time adjustments to training programs, reducing the risk of injuries caused by fatigue or overexertion.

Furthermore, devices such as IMUs and motion capture systems are becoming more prevalent for observing an athlete's biomechanical variations throughout training and events. Research by Di Paolo et al.⁸ emphasizes the

effectiveness of these IMUs in tracking biomechanical changes linked to knee injuries, particularly in activities that exert significant pressure on the ACL. These sensors gather immediate data on movements including knee rotation and joint angles, facilitating early identification of biomechanical risk elements for injuries³. A primary benefit of these technologies lies in their ability to provide real-time feedback, which allows for prompt intervention upon detection of improper mechanics during training.

Regarding injury monitoring, imaging techniques such as shear-wave elastography (an ultrasound-based technique quantifying tissue stiffness), as utilized by Takenaga and his team²⁹, serve as essential instruments for observing tissue adjustments over time. This technology facilitates the evaluation of soft tissue rigidity and the characteristics of muscles and tendons, offering insights into whether an athlete may be susceptible to overuse injuries or muscle strains. Employing such technologies enables monitoring of recovery after an injury and aids in making informed choices regarding return-to-play strategies, according to Takenaga and colleagues in 2015²⁹. Nonetheless, although shear-wave elastography offers valuable information about tissue condition, its cost and complexity hinder its widespread application in real-world scenarios.

Although these technologies hold significant promise for enhancing injury prevention, detection and monitoring, several limitations remain unresolved. A key challenge lies in their practical implementation. While impact sensors and IMUs offer valuable real-time insights, their widespread adoption depends on proper training for medical staff and coaches, as well as the development of infrastructure for efficient data collection and analysis. Additionally, certain advanced technologies, such as shear-wave elastography and 3D motion capture, remain expensive and reliant on specialized equipment, restricting their use primarily to professional teams and well-funded clinics.

Other limitations have been identified regarding data privacy, scalability, and model interpretability. We propose two integrated, data-centric solutions rooted in our prior work:

(i) a privacy-preserving recommender system and federated learning framework^{9,12,17}, which facilitates collaborative model development across institutions without compromising sensitive athlete data; and (ii) an adaptive recommender system architecture¹² capable of generating personalized training recommendations from federated inputs, thus maintaining confidentiality while enhancing decision support.

These innovations directly address the primary challenges identified in this review by reducing implementation costs through decentralized training approaches, enhancing accessibility via scalable federated infrastructures, and increasing interpretability through user-centered, individualized feedback.

Future research should explore the deployment of these solutions using edge computing to ensure feasibility in resource-constrained environments, including youth and amateur sports settings. This could markedly broaden the real-world applicability and societal impact of AI-enhanced injury prevention systems.

CONCLUSION

The findings from this review emphasize the importance of innovative technologies in the detection, monitoring, and prevention of sports injuries. Wearable sensors, motion capture systems, and AI-powered predictive models represent powerful tools for enhancing athlete safety and performance. By providing real-time feedback, personalized injury prevention, and continuous monitoring, these technologies enable coaches and medical professionals to intervene earlier and prevent injuries before they occur. However, for these technologies to reach their full potential, there is a need to overcome barriers related to cost, accessibility, and data interpretation.

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