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Artificial Intelligence and Machine Learning in Athlete Monitoring, Injury Prediction and Performance Optimization: A Narrative Review

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Abstract

Artificial intelligence (AI) and machine learning (ML) are playing an increasingly prominent role in sports medicine, reshaping approaches to athlete monitoring, injury risk assessment, and performance enhancement. This narrative review summarizes current evidence on the application of AI and ML in three closely related areas: training load monitoring, injury prediction and prevention, and the individualization of training. A PubMed search was performed to identify studies published in English between 2019 and 2025. Wearable technologies generate data on internal and external training loads, as well as heart rate variability, providing the foundation for ML-based analyses. Decision trees, random forests, support vector machines, and artificial neural networks are among the methods most frequently used for injury prediction, although their performance varies across sporting disciplines. AI is also being applied to support individualized training, biomechanical feedback, nutritional planning, and return-to-play decisions. Emerging fields of application include sports cardiology, digital twin technology, and 3D-printed sensors. Current limitations include issues related to data quality and interoperability, limited multicenter validation, and concerns regarding ethics and data privacy. AI is increasingly integrated into athlete care, although broader clinical adoption will depend on further validation studies.

Keywords: artificial intelligence; machine learning; athlete monitoring; sports medicine; injury prevention; wearable technologies

1. Introduction

Over the past decade, artificial intelligence has emerged as a major area of development in medicine and sports science. Advances in computing capacity, the growing availability of large datasets, and the miniaturization of sensing technologies have enabled methods once restricted to research settings to enter routine clinical and performance practice. In orthopedics and sports medicine, AI has been proposed as a new tool for injury risk assessment, medical image interpretation, and evaluation of treatment outcomes. Despite this progress, awareness and adoption among clinicians remain limited [1].

Interest in systematic athlete monitoring has also expanded. In modern elite sport, performance depends on the effective management of training load, recovery, and health status. This has accelerated a shift from decisions based primarily on professional experience toward approaches supported by objective data. AI and ML make it possible to analyze large volumes of multidimensional and heterogeneous information that are difficult to address using conventional statistical techniques alone [2].

Sports injuries continue to represent a major challenge. Beyond their physical consequences, they impose psychological and financial burdens and may adversely affect team performance in competitive settings. As a result, injury prediction and prevention have become key areas of AI application in sport [3]. At the same time, growing attention has been directed toward individualized training strategies. Athletes often respond differently to comparable training stimuli, and machine learning models offer a means of incorporating individual physiological characteristics into training prescription and monitoring [4].

This narrative review provides an overview of current applications of AI and ML in athlete monitoring, injury prediction, and performance optimization. It also discusses the principal technical, clinical, and ethical issues that accompany their implementation.

2. Methods

This article was designed as a narrative review. A literature search was conducted in the PubMed database using combinations of the following keywords: artificial intelligence, machine learning, sports medicine, athlete monitoring, wearable sensors, injury prediction, and sports performance. Publications written in English and published between 2019 and 2025 were eligible for inclusion. Both original studies and review articles examining the use of AI and ML in athletic populations were considered. The final selection of literature reflected the thematic scope of the review, with a focus on applications most relevant to athlete monitoring, injury prevention, and performance optimization.

3. Artificial Intelligence in Sports Medicine

3.1. Basic Concepts

Artificial intelligence refers to a broad set of computational approaches designed to perform tasks that typically require human cognition. Within this field, machine learning describes algorithms that learn patterns from data without explicitly programmed rules. Deep learning, a subset of machine learning, is based on multilayer neural networks that extract features directly from raw inputs, including medical images and sensor-derived signals. Predictive analytics is closely related and refers to the use of statistical and computational models to estimate the probability of future events based on available data [1].

In sports science and clinical practice, a clear distinction is made between description, classification, and prediction. Classification models assign observations to predefined categories, such as identifying athletes at increased risk of injury. Regression models are used to estimate continuous outcomes, including expected time to return to play. As these approaches become more widely implemented, their performance and limitations require careful assessment. Integrating AI into multidisciplinary sports medicine teams also introduces practical and interpretative challenges [4, 5].

3.2. Current Applications of AI

Image-based diagnostics remains one of the most established applications of AI in sports medicine. Deep learning approaches, including convolutional neural networks, support automated analysis of imaging data and allow integration of kinematic and physiological parameters in the assessment of injury risk and rehabilitation planning [6]. Developments in imaging techniques, monitoring systems, and algorithm-assisted rehabilitation are increasingly viewed as part of broader changes in athlete care [7].

Computer vision–based biomechanical assessment is also expanding beyond traditional imaging applications. One example is a system used to estimate knee valgus angle during the single-leg squat. Its accuracy and reliability have been tested in handball players, indicating potential use in lower-limb injury prevention [8]. In a similar vein, AI-based applications enable the measurement of countermovement jump height using a smartphone, with results comparable to force platform measurements and allowing assessment of neuromuscular performance outside laboratory environments [9].

4. Wearable Technologies and Athlete Monitoring

4.1. Wearable Sensors

Wearable technologies underpin contemporary athlete monitoring and supply the data required for machine learning models. Body-worn devices such as GPS units, accelerometers, inertial measurement units (IMUs), smartwatches, and heart rate variability (HRV) monitors enable continuous, non-invasive recording of biomechanical and physiological variables. These datasets are subsequently processed using algorithmic approaches to support performance optimization and to estimate the risk of non-contact injury [10].

Evidence from reviews of AI-assisted sensor applications indicates that these methods can detect patterns across physiological, positional, and kinematic variables, with relevance to performance across a range of sports disciplines [11]. In parallel, the combination of biomechanical analytics and machine learning allows evaluation of key performance indicators as well as inter-individual variability under conditions resembling real-world sport settings [12]. The expansion of wearable sensors, cloud-based processing, and AI-based tools has reshaped approaches to sports analysis, with greater reliance on data collected during training and competition in natural environments [13].

4.2. Monitoring of Internal and External Load

Training load monitoring relies on distinguishing between external and internal load. External load refers to measurable outputs of an athlete's activity, including distance covered, number of accelerations and decelerations, and total work performed. Internal load captures the individual physiological and psychophysiological response, typically assessed using heart rate, heart rate variability, and rating of perceived exertion (RPE). A consensus statement on training load monitoring emphasises the importance of considering both dimensions within a shared conceptual framework used by coaches and medical staff [14].

The relationship between internal and external load is not constant and should be interpreted at the individual level, as the same external workload may produce different physiological responses between athletes [15]. Evidence supporting the relevance of precise load quantification also comes from studies examining its association with injury risk. In professional rugby league players, analyses of different training load measures have shown that the choice of load indicators is relevant for injury risk assessment [16].

4.3. Machine Learning in Recovery Assessment

Machine learning is increasingly applied to the assessment of athlete recovery. In a study of long-term endurance training, ML models were used to predict morning recovery status and day-to-day changes in heart rate variability based on data covering training load, sleep, nutrition, and subjective well-being. At group level, a limited set of variables was sufficient, while at individual level the relevant predictors varied between athletes [17].

ML has also been used to estimate subjective exertion. Models trained on wearable sensor data, including heart rate, GPS, and accelerometry, have shown good accuracy in predicting rating of perceived exertion (RPE) in national-level football players [18].

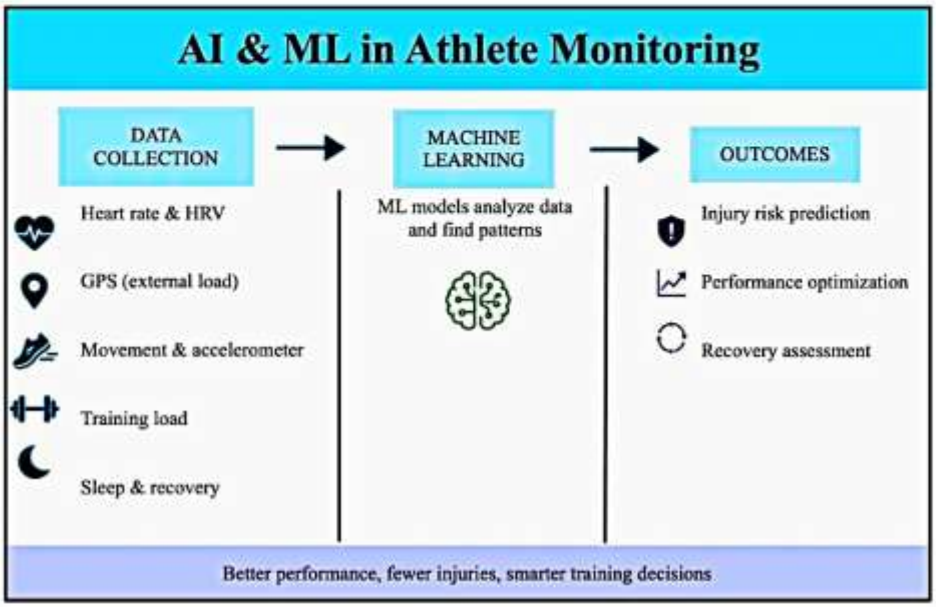

Figure 1. Simplified framework of machine learning–based athlete monitoring using wearable technologies. Source: Authors’ own elaboration based on Section 4. Wearable Technologies and Athlete Monitoring.

5. Artificial Intelligence in Injury Prediction and Prevention

5.1. Risk Factors and Injury Prediction Models

Injury prediction remains one of the most extensively investigated applications of AI in sport. A systematic review of team sports identified artificial neural networks, decision tree classifiers, support vector machines, and Markov processes as the most frequently applied methods, with football, basketball, handball, and volleyball most often represented [19]. Another systematic review of machine learning approaches to injury prediction and prevention confirmed the dominance of tree-based ensemble methods, alongside a relatively limited number of studies meeting strict methodological standards [20].

More recent publications have broadened this field to include deep learning techniques. A comprehensive review of injury risk prediction methods reports increasing use of random forests, convolutional neural networks, and artificial neural networks for analysing complex datasets and informing the adaptation of preventive strategies to individual athlete profiles [21]. Earlier work also described AI as a promising approach for injury prediction, while noting that its performance depends on data quality and on how risk factors are represented, including both biological and external determinants [22].

5.2. Applications Across Sports Disciplines

Machine learning applications in injury prediction vary according to the characteristics of each sport. In football, youth players have been monitored using multidimensional datasets collected over several months, with ML models applied to predict injuries and illnesses [23]. Machine learning has also been reported to enhance the sensitivity of neuromuscular screening tests in identifying injury risk factors in young football players [24]. At the professional level, models combining physiological and mechanical load have been used to estimate the risk of non-contact muscle injuries based on longitudinal training and match data [25].

In volleyball, a personalised approach based on subgroup discovery techniques has been used to identify individual load and well-being indicators associated with overuse-related complaints in elite athletes [26]. In running sports, machine learning has been applied to injury prediction using detailed training logs, integrating GPS-derived objective measures with subjective exertion data. Better performance has been reported for models incorporating load variables from the days immediately preceding injury events [27].

5.3. Injury Risk Monitoring Systems

Integrated approaches for monitoring injury risk are also being developed. One example is a system combining a random forest algorithm with discrete wavelet transform, which uses data from a wearable gyroscope to analyse lower-limb movement in runners. This method showed higher computational efficiency compared with alternative classification approaches [28].

More recent work proposes broader machine learning frameworks that link injury prediction with performance optimisation. These models incorporate explainable AI techniques, including SHAP values, to improve interpretability of outputs used in decision-making by coaching and medical staff, alongside predictive performance [29].

5.4. Challenges in Injury Prediction

Despite encouraging results, injury prediction remains subject to several limitations. Frequently reported issues include small sample sizes, risk of model overfitting, limited standardisation in model development, and inconsistencies in data preprocessing and feature selection. A narrative review of machine learning approaches to injury prediction emphasises the need for standardisation across all stages of model development, from data preparation to evaluation metrics and interpretability [30].

Additional challenges stem from the heterogeneity of sports disciplines and measurement protocols, which limits comparability between studies and the transferability of models across settings. The relatively small number of studies meeting rigorous methodological criteria further supports cautious interpretation of reported performance [20]. Implementation in multidisciplinary environments is also affected by organisational constraints, gaps in technical expertise, and issues of trust in automated systems [5].

6. Artificial Intelligence in Performance Optimization

6.1. Training Individualisation

One of the main applications of AI beyond injury prevention is the individualisation of training. Machine learning–based approaches allow the identification of athlete-specific relationships between training load, well-being, and risk of overload, enabling adjustment of training stimuli to individual profiles [26]. Models estimating subjective exertion from wearable sensor data also support ongoing alignment of training loads with the athlete’s current physiological response [18].

6.2. Biomechanical Feedback

AI enables real-time biomechanical feedback for athletes during training. A wearable sensor system incorporating AI has been developed and tested in hammer throw practice, allowing technical adjustments to be made during execution [31]. This approach is complemented by tools that assess isolated performance variables, such as countermovement jump height measured with AI-based methods [9], and computer vision systems used to evaluate knee valgus angle [8]. These applications provide objective measurements that can support training design and injury prevention strategies.

6.3. Nutrition and Performance

Artificial intelligence is also being applied in sports nutrition. In a study of aerobic gymnastics athletes, training and dietary data were combined and analysed using neural networks and optimisation algorithms to construct a personalised model of nutritional requirements aimed at performance improvement [32]. This reflects increasing interest in integrating nutritional data with AI-based approaches to support a broader framework for athlete performance management.

7. Artificial Intelligence in Rehabilitation and Return to Sport

Rehabilitation and return-to-sport decision-making constitute an active field of AI application in sports medicine. Machine learning is used to monitor rehabilitation trajectories and estimate time to return to activity. One example is the assessment of MLG-R classification performance for hamstring injuries in football players using a machine learning–based approach, in which injury severity was identified as the primary predictor of return-to-play time [33]. Machine learning–based methods have also been proposed for estimating injury risk within sports rehabilitation settings [34].

Interest in personalised rehabilitation is increasing, with AI models adjusting predictions and management strategies to the athlete's individual and evolving condition [6]. The literature suggests that future developments in AI for sports medicine will remain closely tied to return-to-sport pathways, where computational approaches may support multifactorial clinical and performance decisions [35]. Ongoing advances in diagnostics, monitoring, and rehabilitation continue to shape the integration of these tools into athlete care pathways [7].

8. Emerging Areas

8.1. Sports Cardiology

Sports cardiology is a growing field of AI application. AI is used to support interpretation of cardiovascular signals in athletes, reflecting the clinical challenge of sudden cardiac death risk and the difficulty of separating physiological cardiac adaptation from pathological changes in trained individuals [36]. When combined with wearable devices such as smartwatches, AI enables detection of exercise-induced arrhythmias and continuous tracking of cardiovascular parameters, extending the possibilities for monitoring athlete cardiac health [37].

8.2. Digital Twins

Digital twins represent another emerging approach. They are virtual representations of an athlete that integrate data from multiple sources. A digital twin framework has been proposed for taekwondo athletes, combining nutritional information, psychological readiness, and AI-based tools, including wearable technologies and machine learning, into a unified decision-support and holistic monitoring system [38].

8.3. 3D-printed wearable sensors

3D printing has expanded the design space for wearable sensors and their practical deployment. Applications of 3D-printed sensing systems have been reported across disciplines, particularly for monitoring health status and psychophysiological parameters. These approaches allow the capture of individualized, real-time data and support their use in sports psychology as well as in athlete healthcare [39].

9. Challenges, ethical issues, and future directions

Despite rapid progress, broader adoption of AI in sport continues to face several constraints. On the technical side, data quality and system interoperability remain central issues, as model performance depends on the completeness and consistency of input data [1]. The diversity of data sources, coupled with the absence of shared standards, complicates integration and limits comparability across institutions.

Clinically, a key limitation is the shortage of multicenter validation and the relatively modest uptake of these tools in routine practice. Integrating AI into multidisciplinary sports teams requires validated models, but also adequate staff expertise and confidence in decision-support systems [5]. In particular, the value of these tools in return-to-play decision-making will depend on how well they perform under real-world clinical conditions [35].

Ethical concerns center on data privacy and athlete data ownership. Continuous collection of detailed physiological data raises practical questions about storage, access, and secondary use. It also increases the risk of bias when certain populations are underrepresented in training datasets [2]. Addressing these issues requires clear data governance frameworks and careful attention to athletes' interests.

10. Conclusions

1. Artificial intelligence is now embedded in sports medicine, where it is used to support diagnosis, monitoring, and both clinical and training-related decision-making.

2. Its most established applications are in athlete monitoring and injury prediction, which remain the best documented to date.

3. Wearable technologies supply data on internal and external load, as well as recovery, forming a necessary input for machine learning models.

4. Realizing the full potential of AI depends on multicenter validation studies and the standardization of how models are developed and evaluated.

5. Future applications may support more individualized athlete care by combining injury prevention, performance optimization, and rehabilitation, provided that technical, clinical, and ethical barriers are adequately addressed.

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