Movement analysis-based injury prediction model among athletes – a review

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DOI: https://doi.org/10.5114/phr.2025.148700

Received: 25.10.2024 **Reviewed:** 16.11.2024 **Accepted:** 02.12.2024

Abstract

Background: Movement analysis is a multifaceted field that encompasses various methodologies for studying human motion and behavior across diverse contexts, particularly in sports and rehabilitation.

Aims: This review explores the integration of movement screening tools in predicting musculoskeletal injuries.

Materials and Methods: The review highlighted the importance of simulation tools, biomechanical analysis, and the significance of machine learning techniques in predicting injuries. The review explored key parameters such as motor control, strength deficits, and movement patterns, the review underscores the potential of predictive models to enhance athlete safety through targeted injury prevention strategies.

Results: Despite advancements, challenges remain in the accuracy of injury predictions due to inconsistencies in injury classification and variability among athletes.

Conclusions: The review advocates for the development of more refined, sport-specific models that incorporate real-time data analysis and wearable technology, ultimately aiming to bridge the gap in current predictive capabilities and improve athlete health outcomes.

Key words

athletes, biomechanics, movement analysis, musculoskeletal injury.

Introduction

Movement analysis is a diverse field encompassing various methods for studying human motion and behavior in different contexts, including sports and rehabilitation. It has significant applications in health, biometrics, and artificial intelligence [1]. Researchers have made considerable progress in modeling trajectory data, conceptualizing movement patterns, and developing quantitative methods to measure movement parameters [1].

The analysis of human movements is a multidisciplinary field that encompasses various aspects such as biomechanics, cognitive processes, and personality traits. This integration of knowledge allows for a comprehensive understanding of how humans interact with their environment and perform tasks [1]. Movement analysis helps in identifying deviations from normal biomechanics, such as improper joint angles or asymmetrical movements, which can increase the risk of injury.

Movement asymmetry and impairments are closely related to the risk of musculoskeletal injuries for Altered Biomechanics during regular activities, Increased Load on Specific Structures and Impaired Movement Patterns. Research has shown that assessing movement asymmetries can be a useful predictor of future injuries. For example, studies have indicated that athletes with significant asymmetries in their functional movement patterns are at a higher risk of sustaining injuries during sports activities. Movement asymmetry and impairments disrupt normal biomechanics, increase stress on specific body structures, and can serve as indicators of potential injury risk, highlighting the importance of addressing these issues in injury prevention strategies [2].

Movement asymmetry and impairments can lead to altered biomechanics, increased load on specific structures, and overall dysfunctional movement patterns. Studies suggest that athletes with significant asymmetries in functional movement are at a higher risk of injuries during sports activities [2]. Therefore, movement screening aims to detect these dysfunctions before they evolve into injuries. Tools such as Functional Movement Screening™ (FMS™) and Dynamic Movement Assessment™ (DMA™) provide a standardized framework to capture these deviations [2,3].

Injury prediction models gather comprehensive data on athletes, including physical metrics (e.g., strength, flexibility), training loads, injury history, and biomechanical data. It helps in various ways among athletes like prevention of injury by identifying high-risk individuals and allowing for targeted interventions to prevent the injuries before they occur. Therefore, it can be used for optimizing the training program and game management by understanding the factors that contribute to injury risk. Additionally, it can help in enhanced decision making by the clinicians and coaches and thus it is helpful in overall player performance by maintaining the health status and minimizing the injury incidence [2].

It can be used to compare an athlete's data to established norms, helping to identify individuals who may be at a higher risk due to abnormal movement patterns. It is widely used as a real time feedback during the game.

As the complexity of human movement and the multifactorial nature of injury risk become more apparent, there is a pressing demand for comprehensive understanding and innovative approaches to injury prevention. This review aims to consolidate existing knowledge on role of various movement analysis-based injury prediction models and thus, providing a framework for developing more accurate and reliable models. The review seeks to enhance the effectiveness of injury prevention strategies, optimize training regimens, and ultimately improve athlete safety and performance. Furthermore, it highlights the importance of interdisciplinary collaboration in advancing the field and fostering a deeper understanding of the integration of technologies between movement patterns and injury risk.

Aims

The study highlights diverse aspects of movement analysis and its role in injury prediction and prevention. It proposes a structured path for developing more accurate and reliable injury prediction models by integrating existing knowledge and emerging technologies by merging insights from biomechanics and risk assessment. The study promotes innovative, interdisciplinary strategies for improving injury prevention methodologies.

Material and methods

A literature search was conducted through databases including PubMed, Google Scholar, Scopus, and Web of Science from 2014 to 2024. Full-text articles available in English and providing open access were included. The primary focus was on studies describing how movement analysis and related technologies can predict musculoskeletal injuries among athletes.

Lower limb injury prediction using motion analysis and musculoskeletal simulation tools

Lower-extremity sports related injuries can be used to evaluate injury mechanisms, improve performance and techniques, and detect motor control and functional deficits by using motion analysis system [4].

Musculoskeletal modeling and simulation tools provide a practical and quantitative way to investigate the mechanics of musculoskeletal sports injuries by examining the relationships between muscle forces and joint loads during movements with a high risk of injury [4].

The common impairments or parameters to be looked for predicting lower extremity injury includes lumbo-pelvic motor control, hip abductor strength deficit, excessive hip-knee angle, landing mechanism from vertical jump, Q-angle, tight or weak quadriceps, patellofemoral alignment and increased tibial shear force [4].

Movement assessment for predicting musculoskeletal injury risk

Research indicates that the Y-Balance Tests (Lower and Upper Quarter), FMS™, pain provocation tests (specific to injury mechanisms), and ankle dorsiflexion range of motion can collectively assess injury risk among athletes [5].

Such predictive models help create individual athlete profiles based on movement patterns and risk factors, thereby facilitating targeted preventive approaches [5].

Role of data mining and machine learning on injury prediction

Data mining and machine learning are pivotal in injury prediction because they enable the analysis of large datasets to uncover patterns and relationships that might otherwise go unnoticed. Machine learning models—such as decision trees, logistic regression, and neural networks—can be trained on historical data to estimate the likelihood of future injuries based on various input factors (e.g., player statistics, training loads, and physical conditions). Meanwhile, data mining techniques ensure datasets are consistent and comprehensive through processes like handling missing values, normalizing data, and selecting relevant features. With ongoing technological progress, data mining and machine learning can also facilitate real-time monitoring of player performance and health metrics via wearable devices. This capability allows for immediate risk assessment and timely interventions. As a result, integrating data mining and machine learning into injury prediction enhances the ability to forecast injuries, ultimately leading to better prevention strategies and improved athlete safety [6,7].

In one study, the model achieved an injury risk accuracy of 79%, underscoring its effectiveness in identifying key injury risk factors. By normalizing performance metrics relative to teammates, this model provides a quantitative overview of an athlete's strengths and weaknesses, supporting the development of tailored injury-prevention plans. Such targeted strategies can be crucial for reducing the incidence of chronic or career-ending injuries, especially among student athletes [6].

In addition, AI technology can be integrated with wearable devices to track physiological parameters. Advanced motion capture systems can further elucidate the mechanics of movement and their relationship to injury risk through complex biomechanical analyses [7].

Biomechanical analysis in injury prediction

Biomechanics helps in injury prediction by understanding how the body moves; practitioners can identify risk factors for injuries related to specific activities or sports. It examines the forces acting on the body during movement. This includes analyzing ground reaction forces, joint forces, and muscle forces, which can help in understanding how injuries occur. By applying biomechanical principles, athletes can learn proper techniques that minimize stress on the body. Additionally, biomechanics contributes to the design of proper sports equipment and footwear that can reduce injury risk by providing better support and cushioning [8,9].

Results

The study included a total of nine scientific studies. This includes three systematic reviews, two prospective cohort studies, one observational validation study, two literature reviews, and one expert opinion (**Table 1**).

The common screening movements for injury prediction as encompassed in these assessments involve fundamental movements that assess mobility and stability in the kinetic chain, particularly those related to sport-specific actions. Studies found that the dynamic movement assessment™ (DMA™) and functional movement screening™ (FMS™) tools are most commonly used movement screening models in predicting injuries among individuals with different level of physical activity [3]. The Functional Movement Screening™ (FMS™), which is a method used to classify the risk of injury based on the assessment of movement patterns. FMS™ includes seven tests/movements that evaluate different aspects of movement efficiency and stability. These movements aim to identify abnormal movement patterns that may increase the risk of musculoskeletal injuries. the Dynamic Movement Assessment™ (DMA™), which consists of six functional tests that are analyzed through video and focus on unilateral support movements, common in various sports. The FMS tool is validated among different athletic groups however there are so much uncertainty on the diagnostic accuracy (**Table 2**).

The moderate sensitivity and specificity scores don't allow the clinicians to rule in or rule out any specific injuries based on the FMS score. However, the positive and negative predictive values allow predicting or doubting injuries. The AUC score also is a indication of inaccuracy of FMS score on predicting injuries. The larger variability in the odds ratio doesn't confirm the movement impairments as a true risk factor. The FMS tool can serve as a predictor of musculoskeletal injuries however; the uncertainty in the statistical parameters, variability in the injury classification, and the indiscrimination of type of athletes keeps the clinicians in a debatable situation. Similarly, the other tool dynamic movement assessment due to the recent development and a smaller number of studies doesn't provide any statistical interpretation [2-4].

Table 1. Characteristics of included studies.

Authors	Study design	Purpose	Result & findings
Bullock et al. 2021	Systematic review	To evaluate the methodological quality and completeness of existing MSK injury prediction models in sports	The existing models are of poor quality, high bias in nature and they lack external validity. So, there is a need to develop an integrated dynamic predictive model
Seow et al. 2020	Systematic review	To identify and assess the predictive performances of the existing MSK injury predictive models	The existing models are having poor predicting abilities. So, there is a need to develop a robust injury prediction model with standard methodological characteristics
Bunn et al. 2018	Systematic review	To find out the association of DMA & FMS tools with MSK injury risk	There may be association but it lacks specificity and there are too much of uncertainty in predicting injury
Gogoi et al.2021	Prospective cohort	Gait kinematic parameters to predict running related MSK injuries	ROM and symmetry index parameters can increase the likelihood of injuries
Teyhen et al. 2020	Prospective cohort	Assessment of MSK injury based on the risk factor analysis	Prior injury, inadequate recovery, reduced ROM, painful movements, low scores in performance test batteries can be useful in predicting MSK injuries
Henriquez et al. 2020	Observational validation study	Role of machine learning to predict lower limb MSK injuries in athletes	The data mining and machine learning methods are highly capable enough on predicting injuries by accessing a large database
Bulat et al. 2019	Review	Use of MSK simulation models on predicting lower limb MSK injuries	The MSK simulation models can provide a quantitative information related to the mechanism of MSK injuries
Kakaval et al. 2019	Review	Role of AI technology in sports trauma prediction	AI technology can be integrated with wearable devices and in biomechanical analysis to predict injury
Chad Cook 2016	Expert opinion	Existing systems on predicting MSK injury	The future predictive model should be a dynamic and integrated with both internal and external risk factors.

Abbreviations: MSK – *musculoskeletal*, FMS – *functional movement screening*, DMA – *dynamic movement assessment* ROM – *range of motion.*

Table 2. Diagnostic accuracy of FMS.

Sensitivity (SN)	2-68%
Specificity (SP)	38-69%
Positive Predictive Value (PPV)	19-91%
Negative Predictive Value (NPV)	28-85%
Area Under Curve (AUC)	0.42-0.68
Odds Ratio (OR)	0.53-11.67
Risk Ratio (RR)	1.86 (OVERUSE INJURIES) 1.49 (TRAUMATIC INJURIES) -0.5 – 2.73 (ANY INJURY)

Discussion

Injury prediction models depend on thorough movement screenings and consistent participant selection. However, developing a universal model is challenging because each sport has its own injury mechanisms, and injuries are influenced by a range of physical, psychological, and environmental factors that can be difficult to capture in a single framework. Interdisciplinary collaboration improves our understanding of injury risk, and individualized prediction models—tailored to players' specific characteristics—can further enhance prevention strategies. Long-term studies that track athletes over extended periods offer insights essential to creating robust, generalizable models. In addition, testing across different sports, levels of play, and demographic groups can broaden the applicability of these models, while analyzing unique movement patterns helps pinpoint key injury risk factors. AI-driven insights, combined with real-time data and wearable technology, facilitate continuous innovation in machine learning (ML) for sports. By considering athlete-specific profiles and real-time performance data, personalized injury models can more accurately assess injury risk [3,9,10].

Sports injuries unfold within dynamic systems that include both internal factors (e.g., physical condition) and external factors (e.g., environment, equipment). Notably, field type and training compliance often exert a stronger influence on injury risk than baseline physical attributes. Conventional injury predictors can be excessively narrow, ignoring the natural variability among athletes and sports. Consequently, broader constructs—such as strength and motor control—are likely more effective than rigid numerical thresholds in identifying at-risk athletes. Overall, these findings highlight the complexity of sports injury prediction and underscore the need for advanced, dynamic modeling approaches [9–11].

Study limitations and future scopes

Despite the availability of various predictive models, inconsistencies in injury classification and variability in technical methodologies continue to hinder accurate injury prediction. Consequently, future predictive models should emphasize sport-specific requirements and standardized technical analyses, focusing on more homogeneous athlete groups and uniform injury definitions.

Additionally, integrating advanced technologies that capture both internal (e.g., biomechanical, physiological) and external (e.g., environmental) risk factors will be crucial for developing more robust predictive frameworks.

At the outset, this review used the PECO (Population, Exposure, Comparison, Outcome) format: P (athletes), E (baseline movement impairment), C (no movement impairment), and O (injury prediction). The original aim was to investigate the current updates on injury prediction models for athletes with or without movement impairments. However, due to limited evidence encompassing both exposure and non-exposure conditions, the question was reframed to: "What are the latest updates on movement analysis-based injury prediction models among athletes?"

Conclusions

The review concludes that despite the availability of various predictive models for injury risk, inconsistencies in injury classification and variability in technical aspects hinder accurate predictions. It suggests that future predictive models should be developed to address sports-specific requirements and mechanisms, alongside standardized technical analyses with more homogeneous athlete groups and injury types. Additionally, there is a call for integrating these models with technology to account for both internal and external risk factors, ultimately aiming to improve the accuracy and effectiveness of injury prediction in sports.

Declarations

Ethical Consideration: Ethical clearance was not obtained for this study as it does not include any human or animal participants and this consists of a review process of existing literatures.

Clinical Trials: This study was not registered as a clinical trial as it did not involve investigational products or interventions that would classify it under clinical trial regulations.

Conflict of Interest: The authors declare no conflict of interest. The study was conducted independently and without any influence from external organizations or entities.

Funding Sources: This research received no external funding and did not receive any grants or financial support from external sources, including non-profit organizations. The study was conducted using the internal resources of the institutions involved.

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