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EDITORIAL

Beyond the Male Standard: The Role of Artificial Intelligence and Wearable Technology in Tailoring Injury Prevention for Female Athletes

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Introduction

An elite female athlete has a ninefold increased risk of sustaining an anterior cruciate ligament (ACL) tear as compared to their male counterpart (Fox et al, 2020). This significant disparity applies to most soft tissue sports injuries (Hardaker et al, 2024), leading to potential loss of earnings and career setbacks as well as a substantial psychological burden on the athletes (Tranaeus et al, 2024).

There is some insight into the biomechanical reasons for this discrepancy. Females experience greater valgus strain and anterior traction on the ACL due to an increased Q-angle, acetabular anteversion, and neuromuscular dominance of the quadriceps over the hamstrings (Mancino et al, 2024). Hormonal factors also play a role, with surges of relaxin following oestrogen peaks increasing systemic ligamentous laxity (Raj et al, 2023).

Despite some understanding of these unique biomechanical, neuromuscular and hormonal differences, the female athlete is still largely subjected to injury prevention and rehabilitation protocols which have been standardised based on the male phenotype (Cowan et al, 2023; Silvers-Granelli et al, 2015).

Wearable devices, combined with recent advances in artificial intelligence (AI), offer the opportunity for in-depth analyses of the distinct female biomechanical characteristics during training. This data can help understand injury patterns, and help in the development of tailored injury prevention and rehabilitation protocols.

Gathering the Data: Wearable Devices and Image Capture Systems

Effective injury prevention hinges on understanding the biomechanical risk factors unique to each athlete. Traditional methods of assessment, often confined to laboratory settings and based on male-centric models (Cowan et al, 2023), are limited in their applicability. Wearable technology has emerged as a means to gather real-world, dynamic data at scale, providing comprehensive metrics on gait, kinetic analysis, biomechanical alignment, and neuromuscular control (Chidambaram et al,

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2022). These insights are critical to developing sex-specific prevention and rehabilitation strategies.

Inertial measurement units (IMUs) have been utilised to understand general and individual gait patterns (Rivera et al, 2024) by providing data such as tibial acceleration, compensatory hip movements and stride asymmetry, improving risk stratification of injuries such as ACL tear (Richter et al, 2019). A recent systematic review of IMUs for gait analysis found that only 3 of the 121 extracted studies focused on analysing differences between male and female gait patterns, indicating a major research gap in sex-specific gait analysis (Mason et al, 2023).

IMUs in conjunction with 3D motion capture systems dynamically assess limb alignment. Research utilising these technologies has identified correlations such as increased knee abduction angles, which are associated with a higher rate of ACL rupture among female volleyball players (Hewett et al, 2005).

Force distribution during dynamic activities can be monitored with the use of force plates and pressure insoles. This has yielded insight into the impact of ground reaction forces and dissipation of landing forces on the risk of ligament tears such as the ACL (Cacolice et al, 2020) and anterior talofibular ligament (ATFL) (Boey et al, 2022).

Electromyography (EMG) and dynamometer data have been used to identify muscular activation patterns associated with increased injury risk as well as guiding rehabilitation protocol. Neuromuscular metrics have recorded slow reactivation of hamstring function post ACL reconstruction (Cui et al, 2023), as well as insight into the best exercises for specific targeted muscle activation (Moiroux-Sahraoui et al, 2024; Baldim et al, 2024).

Current Applications of AI

Comprehensive biomechanical datasets derived from IMUs, force plates and EMG studies pave the way for the integration of AI to detect complex patterns and enable personalised injury prevention, risk stratification and tailored rehabilitation (Andriollo et al, 2024; Lisacek-Kiosoglous et al, 2023).

Significant progress has been made in applying machine learning (ML) techniques on IMU data to identify patterns of fatigue through gait analysis, achieving a 90% accuracy rate (Baghdadi et al, 2018). Additionally, support vector machine (SVM) models have been trained to accurately identify ankle sprain motions with a 91% accuracy (Chan et al, 2010). These advances carry significant implications for real-time injury prevention strategies (Teoh et al, 2024).

Convolutional neural networks (CNN) used in conjunction with motion capture systems have been used to predict dynamic joint loads with an 89% accuracy as compared to laboratory force-plate equipment, further increasing the feasibility of on-field ACL risk assessment (Johnson et al, 2019). The same motion capture system has been used alongside neural networks to identify patients with incompetent ACL during a range of functional activities such as the single leg hop, achieving a classification accuracy of up to 84% (Richter et al, 2019).

Machine learning techniques in Major League Baseball predict injury risk and anatomical location with an area under the curve (AUC) of 0.65–0.76 (Karnuta et al, 2020).

How AI Can Close the Gap

The ability of AI to process large datasets and generate individualised output holds considerable promise, although further clinical validation is necessary, particularly within female athlete populations. Wearable monitors can be used to ascertain individual risk factors for each athlete, such as the biomechanical and muscular imbalances highlighted in this discussion. Whether gathered in a lab or through sophisticated on-field dynamic biomechanical analysis, this data holds valuable information to coaches, clinicians and physiotherapists. Understanding each athlete's unique profile, enables the development of customised training programmes designed to mitigate injury risks by focusing on specific vulnerabilities, through targeted neuromuscular training or adjustments in sporting techniques.

The transformative potential of AI could revolutionise recovery training protocols. Through continuous monitoring of gait patterns and muscular activation, AI-driven rehabilitation tools can closely track progress of recovery, detect fatiguability, movement asymmetry and compensatory movements that increase re-injury risks. These tools can then dynamically adapt rehabilitation protocols to optimise recovery. Modelling time-series athlete data could individualise return-to-play timelines, balancing risk of premature return with avoiding unnecessary downtime.

However, realising the full potential of AI in this field is not without its challenges. AI systems demand extensive data inputs to ensure their outputs are generalisable. This necessitates widespread adoption of wearable technology across all athletic levels, from recreational to elite. Male dominance in sports and research (Cowan et al, 2023) risks biasing AI outputs. Therefore, it is crucial to collect data from a diverse demographic distribution to mitigate these biases, including emerging areas such as injury patterns in transgender athletes (Miro et al, 2023).

Conclusion

Female athletes face a disproportionately high burden of soft tissue injuries, yet continue to be managed using frameworks developed around the male phenotype. Wearable technologies, combined with AI, offer the opportunity to develop personalised, sex-specific interventions. However, realising this potential requires deliberate efforts to build inclusive datasets, with increased representation of female athletes across all sporting levels. Funding bodies and sporting organisations must prioritise this work. With strategic investment and validation of AI models across diverse populations, sports medicine can move beyond the male standard towards genuinely personalised care.

Key Points

- Female athletes experience a significantly higher burden of soft tissue injuries compared to male counterparts.
- Current injury prevention and rehabilitation protocols remain largely standardised around male biomechanical models.
- Wearable technologies enable the collection of real-world biomechanical and neuromuscular data at scale.
- Artificial intelligence can support personalised injury prevention strategies but requires further clinical validation.
- Diverse, sex-specific datasets are essential to ensure AI models are representative and generalisable.
- Future research must prioritise female athletes and emerging populations, including transgender athletes, to drive equitable progress.

Availability of Data and Materials

Not applicable.

Author Contributions

ZY: Conceptualisation, Writing—Original Draft, Writing—Review & Editing. AP: Conceptualisation, Writing—Original Draft, Writing—Review & Editing. AF: Conceptualisation, Writing—Original Draft, Writing—Review & Editing. FSH: Conceptualisation, Supervision, Writing—Review & Editing. All authors approved the final manuscript and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Ethics Approval and Consent to Participate

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Conflict of Interest

The authors declare no conflict of interest.

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