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Evaluating Wearable Technologies in Football: A Literature Review on Accuracy, Contextual Adaptability and Performance Monitoring

Ruolan Wang[1*], Haoyang Zhan[2]

[1]*School of Sport, Exercise Medicine, Loughborough University, Leicestershire, United Kingdom*
[2]*Sports Institution, Loughborough University, Leicestershire, United Kingdom*
**Corresponding Author. Email: rl.macey.wang@gmail.com*

Abstract. With the advancement of sports technology and the evolution of various athletic disciplines, demands for wearable devices in competitive sports settings continue to rise. Wearable technology has become central to performance monitoring in football, yet its accuracy, contextual adaptability, and usability across competitive levels still present areas for development. This paper employs a literature review methodology to examine GPS/GNSS systems, foot-mounted IMU sensors, and ECG/PPG-based heart rate monitors, analysing their efficacy, application scenarios, and limitations. It concludes that each device type demonstrates distinct advantages in specific contexts—GPS for outdoor tracking, IMUs for micro-movement detection, and ECG for physiological monitoring—highlighting the necessity for multi-sensor integration and standardised frameworks to enhance future applications.

Keywords: Football Technology, Wearable Sensors, GPS and IMU Tracking, Performance Monitoring

1. Introduction

With advances in technology and scientific training, wearable technology has become central to modern sports science, supporting the quantification of athletic performance, monitoring of training loads, and reduction of injury risks. Football's characteristics—intermittent high intensity, frequent changes of pace, and complex tactical dynamics—present significant challenges in accurately capturing both external and internal loads. Devices such as GPS vests, foot-mounted inertial measurement units (IMUs), and chest-strap electrocardiograms (ECGs) are widely adopted by professional clubs, with academies and amateur teams increasingly utilizing them in recent years [1].

Recent studies indicate that GPS systems demonstrate good accuracy in outdoor 11v11 football matches but exhibit reduced performance in indoor or semi-enclosed environments [2]; foot-mounted IMUs are sensitive to micro-movements but face credibility challenges [3]; and chest-strap ECG remains the gold standard for heart rate monitoring [4]. Furthermore, data ecosystems remain

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closed between brands, hindering system integration and long-term usage. These issues underscore the necessity for next-generation devices that combine high accuracy, robustness, and usability.

This paper presents a structured literature review of football wearables, focusing on their accuracy, reliability, and applicability across different match environments and competitive levels. By synthesising recent research findings, we aim to provide a balanced perspective on the strengths and limitations of existing technologies.

Beyond assessing the current landscape, this review explores future directions for football wearables. These include integrating multi-sensor systems for comprehensive monitoring, designing unified solutions for indoor and outdoor environments, and enhancing measurement precision.

2. Comparison of wearable devices

2.1. GPS-based external load detection

GPS/Global Navigation Satellite Systems (GNSS)vest systems (e.g., Catapult, STATSports) are considered the industry standard for 11v11 football. They reliably measure total distance and sprint metrics with high validity. For instance, comparisons with optical systems demonstrate excellent consistency for total distance (ICC ≈ 0.97) and good consistency for high-speed running and sprint distances. However, GPS devices struggle with very rapid or brief movements [5]. Due to their inherent 10 Hz sampling and filtering capabilities, which smooth abrupt changes, their accuracy in measuring instantaneous acceleration and deceleration diminishes. One study found that during small-sided games, 10 Hz GPS recorded approximately 39% fewer accelerations and 35% fewer decelerations than concurrently used high-resolution inertial sensors [6]. In other words, while GPS is highly accurate for distance and steady running measurements, it may miss instances of rapid bursts or abrupt stops, leading to mean absolute errors exceeding 10% for these metrics [7].

2.2. Foot-worn IMU detailed capture

IMUs, such as Playermaker, offer an alternative approach. These sensors capture acceleration and directional data at high sampling rates (up to 1000 Hz). They enable highly precise detection of events like foot contact, ball contact, and gait transitions. Crucially, IMUs do not rely on satellites, enabling operation indoors or in environments with absent GPS signals. During dynamic training, IMUs typically record more movement events than GPS. By capturing every subtle motion, foot-worn IMUs can detect accelerations and decelerations in player activity more effectively than GPS [6]. Because foot IMUs employ integration algorithms (such as zero-speed update techniques) to continuously track motion, they are better suited to capturing rapid changes. A drawback is that IMUs drift over time – minor positional errors accumulate without an external reference. Regular recalibration or correction (e.g., resetting velocity to zero upon foot contact) is required to ensure IMU data remains accurate over extended periods [8].

2.3. Heart rate monitors (ECG and PPG)

Accuracy variations also exist in physiological monitoring. Chest strap monitors (based on electrocardiogram technology, such as the Polar H10) are widely regarded as the gold standard for exercise heart rate tracking. The wristband's electrodes directly receive electrical signals from the heart, with modern designs (featuring buckle fasteners and silicone clips) ensuring the wristband remains comfortable during vigorous activity. This minimises motion artefacts, enabling chest ECGs to deliver stable, precise heart rate readings even during all-out sprints or interval training (no

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significant loss or lag observed in testing) [9]. In contrast, wrist-worn optical heart rate monitors (based on photoplethysmography, e.g., Apple Watch or Garmin watches) infer heart rate by shining light through the skin. These PPG sensors offer convenience and continuous heart rate data but are more prone to inaccuracies during high-intensity exercise. Movement or muscle contraction generates noise, causing optical sensors to temporarily lose pulse signals [10]. Consequently, wrist-worn devices may exhibit heart rate lag or misreadings during fast running or vigorous activity (a phenomenon typically attributed to motion artefacts and pulse wave detection delays).

3. Challenges in the practical application of wearable devices

3.1. Environmental factors

A key challenge lies in maintaining tracking accuracy across diverse sporting environments. GPS trackers perform optimally outdoors under clear skies, such as during full-pitch 11v11 matches. With unobstructed satellite connectivity, modern GNSS devices can pinpoint player locations with typical errors of 0.5 metres or less. This precision suffices for reliable distance and speed calculations during outdoor training and matches. However, the accuracy of standard GPS devices degrades significantly when used indoors or in partially enclosed spaces. Satellite signals become obstructed, leading to unstable or unavailable GPS data. In indoor five-a-side football pitches or covered training facilities, GPS errors can increase dramatically, often rendering precise measurements unfeasible [11]. In such scenarios, teams must turn to alternative tracking technologies. One option is to rely purely on IMUs for indoor sports tracking. IMUs are unaffected by satellite signals, enabling sensors on players' feet or torsos to continue recording acceleration, jumps, and turns indoors. However, as noted, IMU-only tracking develops drift over time and lacks a true positional reference; during extended futsal matches, distance and position estimates may become unreliable without calibration.

3.2. Athlete comfort and safety considerations

Player safety remains paramount. Article 4 of the FIFA Laws of the Game stipulates that players must not wear any items that may cause danger to themselves or others [12]. Consequently, wearable devices must strike a balance between functionality, comfort, and safety in their design. Different device form factors present varying wear experiences and safety risks, directly impacting athlete compliance and data reliability.

Chest straps, commonly used for monitoring heart rate or GPS data, are secured to the torso via elastic bands. During high-intensity or frequent physical contact matches, they may slip or cause skin irritation, compromising measurement stability. Wrist-worn devices, such as smartwatches and fitness trackers, are predominantly used during training phases. Their rigid construction may cause injury during collisions, leading to their prohibition in competitive matches. While lightweight, perspiration and arm movements can compromise fit and signal accuracy.

In recent years, foot-mounted sensors (such as Playermaker) have gained popularity due to their lightweight design and high level of comfort. They can track ball contact without compromising feel, though improper securing or protruding casings may still pose injury risks.

Overall, comfort and safety are pivotal to the widespread adoption of wearable devices. Future development should focus on flexible materials, embedded structures, and safety certification to achieve a balance between monitoring performance and athletic safety.

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3.3. Data usability and visualisation

Performance data holds practical value only when coaches and players can comprehend and utilise it effectively. Variations in data processing and visualisation capabilities across different wearables directly impact their application effectiveness during training and matches.

Some high-end systems offer real-time feedback, continuously transmitting data during training sessions. GPS devices commonly used by professional clubs display running distance, speed, and heart rate in real time, enabling coaches to instantly adjust training programmes or personnel arrangements. For instance, when a player's sprint count declines or heart rate becomes excessively high, coaches can adjust intensity levels or make substitutions accordingly [13]. Conversely, many mid-to-low-end devices only export data post-training, generating statistical reports, heat maps, and load analyses to aid coaches in post-match reviews and long-term trend assessments [14].

The disparity becomes even more pronounced in data visualisation. High-end systems like Catapult offer comprehensive analytical platforms where coaches can view detailed charts via cloud dashboards, compare player performances, tag key events, and export raw data for secondary analysis. These systems visually represent player movement trajectories and physical load through dynamic graphics, enabling holistic training evaluations [13]. In contrast, consumer-grade devices (such as basic GPS units or smartwatches) offer simplified visualisation capabilities, typically providing only basic statistical charts that fall short of professional analytical requirements. More critically, data from some devices remains locked within proprietary applications, restricting export and cross-platform utilisation [14].

3.4. Economic cost and accessibility

Economic cost is a key factor influencing the adoption of wearable technology in both elite and grassroots football. Professional-grade tracking systems are expensive, requiring substantial investment to equip an entire team with GPS vests or UWB tags and associated software subscriptions [2]. Beyond hardware costs, ongoing licensing for data analysis and cloud storage constitutes a long-term expenditure, confining such systems primarily to high-level clubs like top leagues and national teams, while amateur or youth teams often find them unaffordable.

To lower barriers, some manufacturers offer budget-friendly solutions at the grassroots level. For instance, Catapult's Catapult One system charges approximately $150–180 per player annually, providing basic performance metrics and an online dashboard [13]. Such devices enable semi-professional and youth teams to access fundamental load data, though their sampling rates, sensor counts, and software capabilities are typically limited, offering only simplified analysis. Grassroots coaches must balance precision, functionality, and budget when selecting equipment, with some clubs even employing smartwatches or mobile applications for basic movement tracking as alternatives to costly systems.

Overall, wearable technology has made significant strides in quantifying exercise load, yet device fragmentation, scenario adaptability, and regulatory compliance remain key challenges. Future development should focus on multi-sensor fusion, cross-scenario adaptability, and standardised platforms to achieve a balance between high performance and cost-effectiveness

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4. Future development directions for wearable devices

4.1. Multi-sensor integration and unified platforms

Wearable systems should evolve towards multifunctional integrated solutions, tightly integrating GNSS (GPS/Galileo), UWB/LPS, foot-mounted IMUs, and physiological sensors such as HR/HRV monitors into a single terminal. This reduces the need for athletes to wear multiple devices simultaneously and enhances data continuity across sporting disciplines. Recent research indicates that in team sports scenarios, multi-level data fusion can enhance positioning accuracy by over 40% and improve signal quality by 8-10 dB while maintaining real-time responsiveness [15].

4.2. Cross-environment capability through hybrid positioning

Adaptive robustness necessitates seamless adaptation between indoor and outdoor environments. During outdoor eleven-a-side football matches, preference should be given to GNSS, whereas in indoor or semi-enclosed settings, Ultra-Wideband (UWB) or Vision-Inertial Odometry (VIO) may be employed. Optimising factor graphs or extending Kalman filters through tight coupling with IMUs, combined with techniques such as zero-velocity update points (ZUPTs) and online self-calibration, can suppress drift and ensure smooth transitions between indoor and outdoor environments. This hybrid approach enables continuous tracking without performance gaps [15].

4.3. Standardisation and compliance

Engineering development must balance the dual constraints of standardisation and safety. Adherence to the FIFA Electronic Performance and Tracking System (EPTS) Quality Plan and standardised data formats is essential for cross-brand comparability and interoperability. The use of public benchmarking protocols reporting error distributions across different speed ranges should be encouraged to establish transparent quality tiers. Concurrently, adherence to the International Football Association Board (IFAB) Laws of the Game (Law 4) concerning equipment safety is non-negotiable: devices must not "constitute a hazard" to the wearer or opponents [12]. This underscores the importance of ergonomic design, material safety, and certification pathways, with FIFA-approved lower-limb wearables emerging as a promising future development direction.

5. Conclusion

This study examined the accuracy, situational adaptability, comfort, data availability, and economic viability of wearable technologies in football. Findings indicate that despite significant technological advances, limitations persist in environmental adaptability and standardisation. GPS and UWB systems demonstrate stable performance outdoors, and IMUs excel in micro-movement monitoring, while chest-strap ECGs remain the mainstream tool for physiological monitoring. This supports the hypothesis that different device types possess distinct advantages in specific contexts.

The study synthesised evidence across competitive levels and device types, highlighting the potential of hybrid integrated systems for enhancing performance monitoring. For coaches and practitioners, findings underscore the importance of aligning device selection with training contexts, while calling for unified validation standards and adherence to FIFA/IFAB regulations.

The primary limitations of this study lie in its reliance on secondary literature and non-standardised validation methods, coupled with the absence of large-scale field comparative trials. Future research should focus on novel wearable solutions such as multi-sensor fusion, hybrid

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positioning algorithms, and electronic textiles, while establishing standardised benchmarking systems to enhance cross-brand and cross-environment interoperability. Overall, this study offers fresh perspectives and directions for the advancement of football wearable technology.

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