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# Smart Football Footwear: A Narrative Review of In-Shoe Sensors for Biomechanical Monitoring and Injury-Risk Assessment

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## ABSTRACT

In football, the lower extremity is constantly subjected to repeated high-rate loading through sprinting, accelerating, decelerating, cutting, jumping and landing, and ball-related activities. Laboratory devices for measuring athlete–surface interactions give only a partial picture of the loading of real-world shoes. In-shoe sensor systems, such as pressure sensors and hybrid systems (pressure and inertial sensors), are a practical solution for measuring the loading and movement of the plantar surface during sport-specific tasks. A narrative review of the foot–ground impact–injury pathway and the use of in-shoe sensors to monitor a player's biomechanics while playing football is undertaken. Relevant literature was identified by searching PubMed, Google Scholar, and Scopus databases with terms associated with football, plantar pressure, in-shoe sensing, footwear biomechanics, and injury-risk monitoring. Evidence shows that cutting and change-of-direction techniques can redistribute loading through the plantar regions to the medial areas of the foot, and footwear characteristics and stud–surface interaction can affect traction and joint loading. Modern in-shoe systems are capable of analyzing peak and mean pressure, pressure–time integral, contact area, centre-of-pressure trajectory, loading asymmetry and temporal gait variables. Despite this, making these measures predictive of injury is still difficult, as injury is multifactorial, most pressure insoles do not measure shear forces, there is variation between calibration protocols under sport-specific loading rates, and prospective validation has been limited in football. A sparse, yet strategically placed pressure-sensor array, possibly in conjunction with other sensing modalities like inertial measurements, could offer a practical compromise of wearability and regional load measurement; however, further validation on football-specific testing is needed before an optimal number of sensors and optimal placement can be determined. Standardized protocols, multimodal sensing, longitudinal datasets, and validated algorithms relating sensor-derived loading patterns to clinically relevant injury outcomes are areas that future research should focus on.

**Keywords:** *football; soccer; smart insole; plantar pressure; wearable sensors; biomechanics; football footwear; impact; injury risk; load monitoring*

## 1. INTRODUCTION

Football includes a lot of low-intensity activity and high-intensity activity, including sprints, quick acceleration/deceleration, cutting, jumping, and landing. These actions involve complex forces at the shoe-surface interface and repetitive mechanical loading of the foot, ankle, knee and proximal lower limb. Football boots are more than just protective equipment; they can also affect foot traction, proprioceptive feedback, plantar pressure distribution and lower extremity loading; the mechanical configuration of the shoes can thus alter the in-game biomechanics and performance properties of the shoes and athlete (Tourillon et al. 2024).

The high risk of lower extremity injuries in football stems from the repeated exposure of athletes to sprinting, deceleration, cutting, jumping, landing, and physical contact. There is a large percentage of time lost in football due to injuries to the thigh, knee, ankle and foot, and injuries to the anterior cruciate ligament, ankle sprain and metatarsal injury can cause a significant amount of time away from training and competition. This injury burden implies the need for field measures that are able to repeatedly characterise loading of the lower extremities during football-specific activity (Fares et al., 2022). Biomechanical monitoring should be considered additional to, and not a replacement for, clinical and epidemiological risk assessment for injuries, instead of being a tool for diagnosis or prediction.

The traditional way of biomechanical assessment is very dependent on force plates and motion-capture systems, as well as pressure plates in the laboratory. The technologies offer good quality measurements, but require the athlete to be in a limited capture volume and do not represent the unpredictable movement patterns associated with football, which are multidirectional. In-shoe sensing overcomes this by placing measurement technology at the foot–footwear interface. Wireless pressure insoles can measure repeated steps and dynamic foot movements during sports and can be uniquely used for footwear effects assessment and field-relevant loading (Alahaidib et al., 2025) and are therefore ideal for this purpose.

Plantar-pressure measurement systems, commercial pressure sensors and emerging insole technology have been explored in sport, health and clinical applications in previous reviews. These reviews give valuable information on sensing principles, calibration, reliability and design of wearing systems (Abdul Razak et al., 2012). However, comparatively less attention has been directed to the integration of this evidence specifically with football movements, football footwear, shoe–surface interaction and interpretation of injury risk. The present review will thus focus on the football-specific setting and additionally on a proposed sparse-sensor approach for longitudinal monitoring.

This review aims to collate the biomechanical justification, technologies used for in-shoe monitoring, outcome measures, and injury-related applications of in-shoe monitoring in football. The evolution from foot–ground impact to tissue loading and injury risk is emphasized, and design implications for multi-sensor systems like a six-sensor insole for football are discussed.

## 2. REVIEW METHODOLOGY

### 2.1 Literature search and study selection

This narrative review was conducted to identify literature concerning football-specific plantar loading, in-shoe pressure measurement, wearable sensing, footwear–surface interaction, and injury-risk monitoring. Literature searches were conducted using PubMed, Google Scholar, and Scopus for publications available from 2010 - 2026. Search terms included combinations of "football," "soccer," "in-shoe," "smart insole," "plantar pressure," "wearable sensor," "football footwear," "biomechanics," "traction," "injury," "injury risk," and "load monitoring."

Studies were eligible to be included if they explored populations of football players or soccer players, football-specific movements, in-shoe or wearable plantar-pressure systems, footwear–surface interactions, or sensor-based biomechanical monitoring of relevance to football. Where relevant, technical and methodological studies on in-shoe sensor technology were also included that included information on in-shoe sensing principles, calibration, validity and/or reliability, and/or signal processing. Studies were excluded if they were not related to lower extremity biomechanics, did not contain data relevant to the goals of this review, involved non-football populations with no information available on wearable/in-shoe sensing or measurement methodology, were editorials or letters to the editor, conference abstracts, or opinion pieces with no primary or methodological data available, or were duplicate publications. A few studies were not included because they were not methodologically comprehensible. When an English-language full text was available, no language restriction was imposed.

### 2.2 Limitations of the review methodology

A narrative review methodology was employed. The search process was not intended to be comprehensive; however, all potentially relevant studies were considered, as multiple sources of literature were considered. This may therefore have introduced a selection bias, a publication bias, different terminology in different disciplines, and access to full-text publications. Furthermore, there was heterogeneity in the type of sensor systems used, the calibration methods, the type of football activity, the types of surfaces, and the group of participants across studies, as well as across the various biomechanical outcomes reported.

## 3. FOOT–GROUND INTERACTION IN FOOTBALL

### 3.1 Football-specific loading

The forces on the inside of a football boot are dependent on the movement, the speed, the foot strike, the playing surface, and the type of studs and individual technique. Football presents a great mediolateral and rotational requirement as opposed to steady running. Wong et al. 2006 conducted a classic in-shoe movement study of soccer-specific movements in 15 male football players during running and cutting movements on an artificial turf field. Both sideward and 45° cutting resulted in higher pressures in some

of the medial plantar areas than controlled running. These results highlight the limitations of using straight-line gait to characterize the plantar-loading requirements of football-specific footwear and motion.

Further research on plantar loading in the context of football has confirmed this observation. Research investigating the biomechanics of running, sprinting, cutting, kicking, and other soccer-specific actions has found significant differences in plantar-pressure distribution throughout the running action, especially across the medial forefoot, lateral forefoot, heel, and toe regions. Eils et al. investigated plantar loading during soccer-specific movements and found that plantar loading in the various regions was different depending on the movement (Eils et al., 2004). Additionally, DeBiasio et al.'s study revealed that the modified footwear configuration and cutting task significantly affected plantar loading (DeBiasio et al., 2013). The results taken together suggest that plantar-pressure can not be described by straight-line running of the foot during football-specific loading, and that when comparing plantar-pressure findings, the type of footwear, surface, task, and direction of movement should be reported.

The forces generated more distally are also affected by the interaction between shoe and surface. A study of shoes indicated that modifying the geometry of the studs can affect the amount of rotational resistance and traction provided by the shoe (Villwock et al., 2009). Experimental studies show that outsole and stud design can affect the translational traction, rotational resistance, and loading of the lower extremity. The size and direction of those effects are dependent upon the geometry of the studs, the number of studs, where they're placed and where they're distributed, the playing surface, and the type of movement performed. Thus, the safety or riskiness of individual designs cannot be generalized without referencing the shoe–surface and movement conditions in which they were evaluated (Keshvari et al., 2023). The stiffness, cushioning, upper construction and fit of the soleplate further adjust load distribution and proprioceptive feedback. Therefore, plantar loading should be considered as part of a “kinetic chain” of variables, and not just a foot variable.

### 3.2 From impact to injury

An impact does not automatically lead to an injury. The interaction of external loading and tissue capacity, joint position, neuromuscular control, fatigue, and prior injury/exposure history results in injury. One of the advantages of in-shoe systems is that they can measure repeated external-loading signatures at the time of the athlete contacting the ground. Unusual regional peak pressure, pressure–time integral, excessive loading rates, asymmetry of pressure, change of centre of pressure and pressure contact time are some of the candidate indicators (Chen et al., 2025). These measures can provide evidence of changing movement strategies and/or overload within a particular region, but should not be interpreted as a diagnosis, but as a risk indicator.

This is very important to distinguish. Previous studies in running have found relationships between plantar pressure variables and injury status, but there is no consistency in these relationships (Mann et al. 2016). General literature surveys of sports wearables also find that the technology is developing at a greater rate than potential evidence showing wearables-derived metrics to be correlated with a real

musculoskeletal injury (Alzahrani et al., 2026). The plantar-pressure results of football-specific studies should thus not be interpreted as actual risk factors for the development of injuries, but rather as potential biomechanical risk indicators. This sense of caution is all the more important as there is limited long-term evidence available that correlates loading patterns from the sensor with injury. This proposed relationship between external loads in football and internal loads to tissues and possible injuries is summarised in Figure 1.

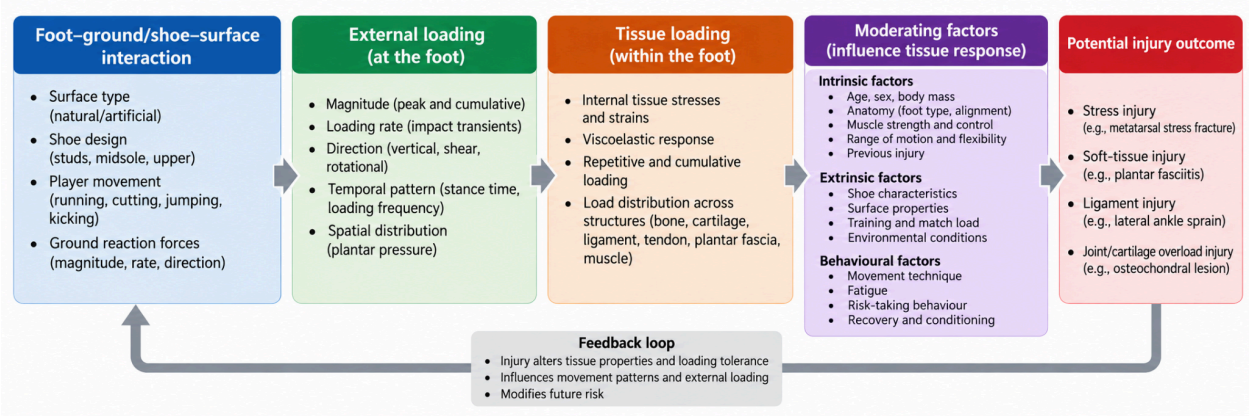



**Figure 1.** Conceptual pathway linking football-specific shoe–surface interaction and external loading with tissue loading and potential injury outcomes. Injury is multifactorial, and sensor-derived plantar loading should be interpreted as one component of a broader risk framework rather than as a direct diagnostic measure.

## 4. IN-SHOE SENSOR TECHNOLOGIES

### 4.1 Pressure-sensing principles

Most in-shoe plantar-pressure systems are based on resistive/piezoresistive, capacitive, or piezoelectric transducers. Resistive sensors are inexpensive, thin, and easy to make, and so are desirable for multi-point applications, but they do have drift and a hysteresis effect with repeated measurements. Capacitive sensors offer good sensitivity and flexibility, and piezoelectric sensors are suitable for dynamic events, but are not suitable for static loading. Other new flexible sensor techniques are also being developed, such as optical sensors (Abdul Razak et al. 2012; Castro-Martins et al. 2024).

In-shoe systems have a wide range of performance characteristics depending on the type of sensor used, the number of sensors, the calibration process, sampling frequency, and purpose. Piezoresistive sensors are desirable for thin, flexible and relatively inexpensive systems, but may exhibit hysteresis, drift, and susceptibility to repeated loading. Capacitive systems can achieve high sensitivity and repeatability, but might be more complex in electronics. The piezoelectric sensor is effectively used for dynamic loading but is generally not a good choice for measuring sustained static pressure (Burnie et al., 2023) . These

attributes should thus be taken into account when considering the intended football movement and outcome variable.

Commercial systems typically employ a sensor matrix with many sensors to develop a plantar pressure map. A smaller number of strategically placed sensors are often employed in research prototypes, however. According to a systematic review done in 2024, the new systems typically consist of four, six, or eight pressure sensors in the in-soles that are removable (Castro-Martins et al. 2024). A few clinical and wearable applications have been explored with sparse pressure-sensor networks, but results from the diabetic-foot application cannot be directly extrapolated to high-speed football activities such as sprinting, cutting, and landing (Ehtemam et al., 2026). The six-sensor setup should thus be considered a hypothesis of engineering design for football and not an optimal architecture. It has to be shown experimentally by a high-density reference system in representative football-specific movements. While the majority of commercially available plantar-pressure insoles measure normal (or vertical) pressure, specialized research systems have been developed that can either estimate or directly record shear forces.

### 4.2 Proposed six-sensor configuration for football

The following six-sensor configuration is proposed as a conceptual engineering framework, and is not to be construed as an established optimum configuration from experimental testing. The aim is to determine if areas of the plantar surface, strategically selected, could be used to obtain useful longitudinal data, while simultaneously minimizing the complexity of the hardware and computational requirements compared to high-density pressure matrices. It is therefore essential to validate the proposed configuration for football, in an experimental setting, before any conclusions can be drawn about its accuracy, clinical relevance, or its superiority over other possible configurations of the football sensors.

Football sensor placement should be based on the movement requirements and anticipated pressure areas. Six regions of practice could be heel, medial midfoot, lateral midfoot, medial forefoot/first metatarsal region, central-lateral forefoot/metatarsal region, and hallux/toe region. The six-sensor arrangement suggested here is thus an engineering design framework and should not be interpreted as a standard for sensor placement. The best layout should be determined in the running, cutting, acceleration, deceleration, and landing phases using a high-density reference system in a pilot mapping process.

An engineering perspective of a football-specific smart insole should be founded on a balance of measurement quality, wearability, and practical deployment. Critical design challenges involve sensor thickness, overall device mass, sampling rate, battery power, wireless data transfer, resistance to repeated high-load stud surface interactions, resistance to sweat and moisture, manufacturing complexity, and cost. The placement of the sensor and electronic components must also avoid interfering with the fit of the boot and plantar feedback. The number of sensors should not be the only criterion for the final configuration, but rather a structured optimisation process, based on biomechanical accuracy, durability, user comfort, power requirements, data-processing requirements, and manufacturability. The proposed regional functions of the six sensing locations are summarized in Table 1.

**Table 1.** Proposed six-sensor regions and their intended biomechanical relevance in football-specific monitoring.

| **Proposed sensing region** | **Biomechanical rationale** | **Potential application** |
|---|---|---|
| Heel | Initial contact during running and landing | Impact timing and rearfoot loading |
| Medial midfoot | Medial transfer of plantar load | Changes in medial loading and COP progression |
| Lateral midfoot | Lateral stability during multidirectional movement | Edge loading during cutting |
| Medial forefoot/first–second metatarsal region | High loading during propulsion and cutting | Medial forefoot pressure and push-off |
| Lateral forefoot/fourth–fifth metatarsal region | Important during lateral loading; clinically relevant to fifth-metatarsal loading | Detection of lateral forefoot overload |
| Hallux/toe region | Terminal propulsion and toe-off | Toe-off timing and push-off pressure |

These six regions are suggested on the basis of their potential biomechanical relevance during football-specific movements, and are not considered the best possible placement. More specific high-density pressure mapping of the relevant areas is needed to identify whether these areas are able to consistently identify the most informative patterns of loading in the region relevant to football. During the soccer-specific tasks, it is recommended to compare the six-sensor setup with a validated high-density plantar-pressure system to propose a valid study. Participants should run in a straight line, accelerate, decelerate, cut, land, plan and execute cuts, run, and kick in a curve. Whenever possible, both natural grass and artificial turf conditions should be tested.

The output of the sensors must be compared with the regional measurements (from the reference system). Intraclass correlation coefficients, Bland-Altman bias and limits of agreement, root mean square error, and other suitable measures of measurement error can be used to quantify agreement. Special consideration should be made for whether pressure peaks between sensors are underestimated or missed between them.

A six-sensor configuration is proposed for football-specific plantar-load monitoring (Figure 2), where the sensors are located at the heel, medial and lateral midfoot, medial and lateral forefoot, and hallux to measure regional loading during football-specific movements.

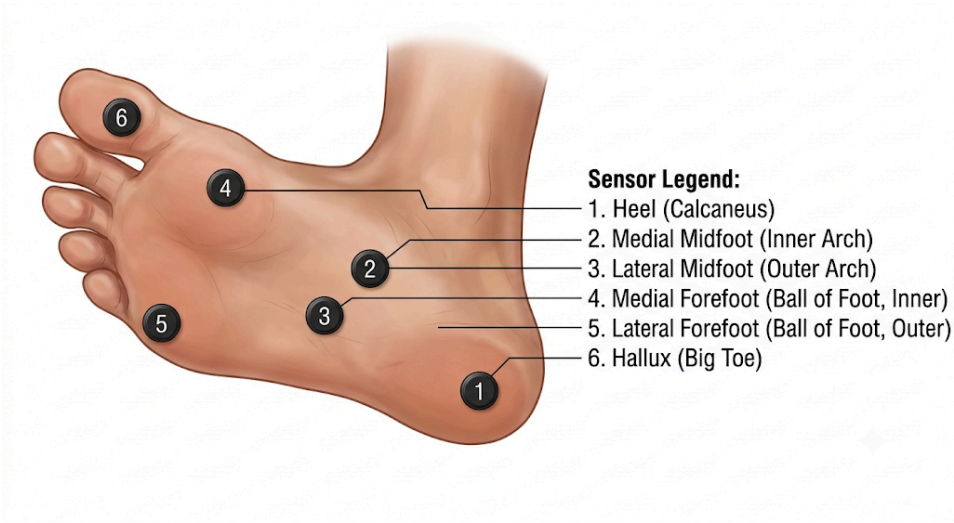



Figure 2. Proposed six-sensor placement for football-specific plantar-load monitoring. The configuration represents a conceptual engineering framework and requires validation against high-density plantar-pressure measurements during representative football movements (Image created using Google Gemini).

### 4.3 Hybrid sensing

The pressure data provides information on the normal loading at the plantar surface and gives very limited information regarding orientation and acceleration of the segments. The addition of pressure sensors to inertial measurement units (IMUs), which are basically accelerometers and gyroscopes, can provide foot acceleration, angular velocity, foot orientation estimates, and event detection. The major benefit of hybrid sensing is that the same plantar-pressure pattern can be produced by various movements, and the acceleration, angular velocity, and orientation information provided by the IMUs can be useful in distinguishing the movement context. IMUs, however, have their own drawbacks such as motion artefact, sensor displacement, and errors in estimation of the orientation of the IMU during a high-impact task (Maggioni et al., 2026).

## 5. BIOMECHANICAL VARIABLES DERIVED FROM SMART INSOLES

The value of an in-shoe system is not just in the sensor; it also depends on the variables derived from the sensor. Common parameters include peak pressure, mean pressure, estimates of force, pressure–time or force–time integrals, contact area, contact duration and centre-of-pressure (COP) trajectories. Flexible

sensor systems can also be used to describe the movement of sports-related gestures, such as stance and time characteristics of gait (Kasai et al., 2024) . Common variables that may be derived from in-shoe plantar-pressure data are summarised in **Table 2**.

**Table 2.** Common biomechanical variables derived from in-shoe plantar-pressure systems and their potential football applications.

| Variable | Interpretation | Possible football use |
|---|---|---|
| Peak pressure | Maximum regional loading | Identify local overload during cutting/landing |
| Pressure–time integral | Area under the pressure–time curve over the defined contact period | Repeated exposure / cumulative regional load |
| Contact time | Duration of stance | Movement strategy and fatigue response |
| Regional load ratio | Distribution across foot | Medial–lateral or forefoot–rearfoot bias |
| COP trajectory | Progression of plantar load | Stability and altered foot-loading strategy |
| Left–right asymmetry | Inter-limb difference | Return-to-play and compensatory loading |
| Loading rate proxy | Speed of force/pressure rise | Impact severity screening |

The sampling frequency should be determined by the biomechanical variable being measured. Variables relating to stance duration or slow changes in plantar pressure may not need such temporal resolution as those variables that aim to characterise the rapid transients of impact or loading rate. Hence, estimates of loading rates must only be used when sampling frequency and sensor response have been established for the length of time and velocity of the football-specific event being measured.

Additionally, to use force measured by plantar-pressure insoles as a proxy for vertical ground-reaction force measured on a force plate, one needs to be aware that the insoles have an area of coverage different from the force plate, the calibration of plantar pressure sensors may differ from that of force plates, and the principle of measurement may differ.

For six-sensor systems, regional ratios or temporal signatures could be more robust than trying to determine a full pressure map. For instance, the medial-to-lateral forefoot loading during a cut, heel-to-forefoot transition time or differences between the left and right for repeated accelerations can be features that can be interpreted while minimizing the computational and hardware complexity.

## 6. APPLICATIONS TO INJURY MONITORING IN FOOTBALL

### 6.1 Foot and ankle loading

Repeated localized plantar loading may lead to discomfort, callus formation, metatarsal stress and overuse symptoms, and sudden alterations in loading may indicate altered mechanics following injury. In-shoe sensors could determine the areas that might have excessive or imbalanced pressure in the football boot itself. They can also assist in comparing boots and insoles/stud configurations of a player (Cho et al., 2023). Most widely used insoles for the plantar surface of the foot, however, measure only the plantar pressure pressing the foot downwards and thus do not directly measure shear loading. This is a major restriction in football as cutting, pivoting and rotational movements can result in significant tangential forces on the foot–shoe interface. There are some special research systems available which can measure shear, but normal-pressure systems are used more frequently.

### 6.2 Knee and proximal lower-limb injury risk

Plantar measurements and knee injury are indirectly related. While plantar pressures cannot quantify ACL strain and knee moments, the loading of the joint can be increased due to high traction, speed of deceleration, and rotational loading. Plantar-pressure measurements can provide complementary information to the timing and distribution of loading on the foot during potentially high-risk movements, but can not directly measure ACL strain or knee-joint moments. Video or motion analysis can be used in conjunction with the pressure data and IMU foot orientation to help improve the biomechanical interpretation (Navacchia et al., 2019). Results from studies on the mechanical properties of football footwear and the type of studs can have an effect on the loading at the joints of the foot, further supporting the importance of considering pressure signatures in the context of the foot–shoe–surface system (Yang et al., 2026).

### 6.3 Fatigue and workload

Fatigue can affect movement strategy, contact timing, and plantar-load distribution; however, the direction and magnitude of these changes are dependent on the task, population, and fatigue protocol (Willems et al., 2012). In-shoe monitoring can provide a means to see if the distribution of load progressively changes in one of the regions during training and/or match play. It would be better to have a player-specific baseline to be able to pick up deviations rather than universal thresholds. These kinds of strategies have potential for use in workload management and should be studied further to understand if these deviations are predictive of subsequent injury or if they are simply normal adaptations.

### 6.4 Rehabilitation and return to play

Rehabilitation and return-to-play monitoring are potential applications for repeated in-shoe measurement. Athletes may protect the injured lower limb or use strategies that reduce the impact of the lower-limb injury, but are not easily detected from the outside. In-shoe measures repeated over time can be used to measure the left–right asymmetry and restoration of sport-specific loading during running, cutting and

landing (Hao, 2024). Serial measurements may also assist in identifying if sport-specific loading symmetry is being achieved over time in rehabilitation. Asymmetry is not to be taken as the only indicator, however, as some inter-limb differences can be considered as normal individual variation (Heshmati et al., 2025). Therefore, return-to-play decisions should be made with an integration of in-shoe data and clinical examination, strength testing, functional performance and athlete-reported symptoms. This objective information may be used in addition to, and should not supplant, strength testing, clinical examination and athlete-reported symptoms.

## 7. VALIDITY, RELIABILITY AND METHODOLOGICAL CHALLENGES

There are trade-offs in the measurement of field usability. In-shoe systems typically offer lower spatial resolution and fewer samples compared to pressure platforms, but have the advantage of being able to measure pressure in the footwear and during dynamic activity in the same location within the footwear over time (Wang & Ni, 2025). One of the prime issues is calibration. The sensitivity of the sensors can change depending on temperature, multiple loading, curvature, footwear fit, and loading rate. A critical consideration of this is that common calibration devices may be capable of measuring at lower loading rates than what are seen during athletic movements, making it important to have sport-specific dynamic calibration (Catalfamo et al., 2008).

Sampling frequency should be adequate to discriminate the smallest biomechanical event and outcome variable of interest. This is especially true for the rapid impact and loading-rate measurements, which need to have more temporal resolution than stance-duration and slower regional-pressure measurements do (Mason et al., 2022). The selected sampling rate should be explained based on validation evidence of the sensor system and the football task to be performed, and should not take a universal minimum frequency for all tasks. The thickness of the sensor and wiring should not significantly affect the fit of the boots or the proprioceptive feedback given by them. When pressure is added to IMUs, GPS, video, or electromyography (EMG), data synchronization becomes important. The type, number, and anatomical placement of sensors, calibration procedure, sampling rate, type of footwear, surface, movement speed, criteria for selection, and signal processing of trials should be reported in the research paper as well. If this is not accomplished, there is a lack of comparison between studies.

Another limitation is related to the interpretation of sparse sensor arrays. A local pressure hot spot may occur between two sensing elements, resulting in the system underestimating or missing the actual maximum pressure. High-density pedobarography should not be viewed as the same as a six-sensor array. Despite the low density, sparse configurations can still be beneficial when attempting to monitor longitudinal progressions through predetermined anatomical regions, but they also reduce the number of hardware components, the amount of data that needs to be stored, and the computing load. Validity requires proper placement of sensors and experimental validation directly for the football.

## 8. DATA ANALYTICS AND INJURY-RISK MODELLING

There is an opportunity for automated analysis of the in-shoe data when repeated data are collected. Raw signals can be transformed to peak values, impulses, timing variables, asymmetry indices, and signatures of movement by feature extraction. These machine-learning models might then be used for action classification, identifying abnormal loading, or even for individual risk state estimation. There is a current need to interpret plantar-pressure data in a more complete way, which is seen as a potential avenue for integrating artificial intelligence as part of the pressure-sensor methodology.

However, injuries are relatively rare events, resulting in significant class imbalance in predictive datasets as compared to the number of non-injury observations collected during longitudinal monitoring. Additionally, models may be prone to overfitting due to small athlete cohorts and high numbers of candidate biomechanical features. Furthermore, due to the small number of athletes and candidate biomechanical features, the risk of overfitting the model could also be increased, meaning that the model might perform well on the development data but perform poorly on a new player. Predictive algorithms will thus need to be tested prospectively and validated in external validation sets before they are used clinically or for performance management. Longitudinal and multimodal is a more defensible approach: future models should combine in-shoe biomechanical data with previous injury history, wellness, strength, playing surface, footwear and workload data; and then be tested in an independent cohort.

## 9. RESEARCH GAPS AND FUTURE DIRECTIONS

Five priorities emerge. First, prospective studies should be conducted specifically for football and be correlated to subsequent injury, not just cross-sectional differences. Second, sprinting, planned and unplanned cutting, deceleration, landing, and repeated fatigue should all be a part of standardized football protocols. Third, the sparse configurations of sensors (including 6 sensor configurations) must be tested against reference pressure matrices and force plates. Fourth, future insoles need to also measure or estimate shear or rotational loading, as normal pressure alone does not fully describe the dynamics of the shoe–surface interaction in football. Fifth, algorithms should now evolve from universal thresholds to player-specific thresholds that include position, foot morphology, boot type, surface, and previous injury.

In-shoe biomechanical measurements must also be interpreted with consideration of population-specific factors. Sex, age, playing level, and prior injury may have different plantar-loading patterns, physical capacity, and injury epidemiology. Therefore, the thresholds established for the adult male players should not be translated to female players or young players. Playing surface should also be taken into account, as in the case of natural grass and synthetic turf, shoe–surface interactions, as well as the traction and loading characteristics, can vary. Future validation studies should thus include the sex and age of participants and test the sensor behaviour within the surfaces most relevant to the target population of footballers.

The design of a sensor should also be athlete-centred. An accurate system that alters the boot fit and adds significant weight and/or requires difficult-to-handle hardware may lack ecological validity. The likely improvement of long-duration monitoring will be achieved through thin, flexible sensors, and onboard processing and wireless transmission with low power (Burnie et al. 2023). Therefore, the ultimate goal

should not be only to gather biomechanical data, but to convert those reliable and trustworthy measurements into interpretable information that could help guide evidence-based decisions by the athlete, the clinician, and the coach.

## 10. CONCLUSION

The combination of in-shoe sensor technology with laboratory biomechanics is an intriguing link between the lab and the real demands of football. Pressure-sensing insoles can measure the plantar loading in the various portions of the foot, and the temporal characteristics of its interaction with ground response, COP behaviour and asymmetry in various sport-specific actions, with the addition of movement and impact information provided by hybrid systems. Experimental evidence already shows that cutting and other football actions result in different loading patterns of the plantar surface and that properties of the footwear affect the shoe–surface interface (Villwock et al., 2009). However, the field has not yet progressed from measuring biomechanical loading to reliably predicting subsequent injury. Injury is multifactorial, most insoles are not able to measure shear directly, and there is limited prospective validation for football-specific insoles.

The placement of a strategically positioned six-sensor insole is an engineering hypothesis that could be tested to simplify hardware and provide information from specific regions of the plantar surface. This, however, cannot be automatically assumed at present based on the number of sensors. The scientific validation will need accurate placement, with the use of a football-specific plantar-pressure mapping system to compare with a validated reference system, adequate temporal resolution, and assessment during representative movements (acceleration, cutting, deceleration, landing). Smart football shoes are not a perfect substitute for an injury detection system, but they could be a part of a comprehensive monitoring system that can detect variations in loading, aid rehabilitation, and provide objective data for personalised systems of injury risk management.

## AUTHOR'S CONTRIBUTIONS:

Dhruva Rojekar conceptualised the study, did a literature survey, wrote and corrected the manuscript.

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