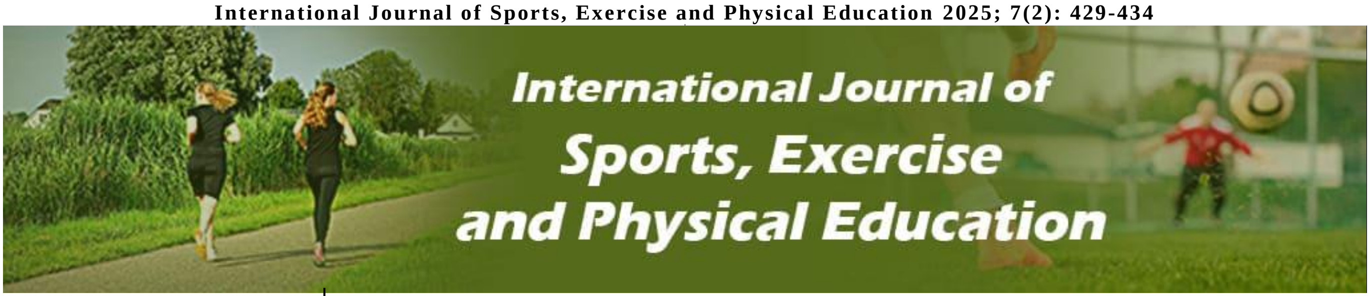

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Use of GPS and inertial sensors for monitoring external load in football players

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Abstract
This article examines the integrated use of Global Positioning System (GPS) technologies and inertial measurement units (IMU) for monitoring the external load of football players, to optimize the training process, individualize workloads, and reduce injury risk. The relevance of the study is driven by the increasing demands on players' physical preparedness and the need for objective control over the intensity of competitive and training activities. The newness of the work lies in the methodical evaluation of the prospects of GPS and IMU as supplementary aids, apart from checking sensor data fusion techniques to attain precise measurement amidst great dynamics and signal unsteadiness. The study made it clear that GPS systems are able to provide spatiotemporal characteristics of movement like distance and speed, intensity zones, or heat maps; on the other hand, inertial sensors can pick up microdynamics related to acceleration or deceleration, change of direction, jumping as well as collision events. Therefore, these technologies produce a very holistic picture of work that can be related to tactical context consideration, recovery monitoring, injury prevention, and training program adaptation to players' characteristics. Limitations were identified as measurement errors, operational conditions, standardization of installation and calibration protocols, and financial and organizational implementation aspects. This article sheds immense benefits to sports scientists, coaches, analysts, and medical staff of football teams who have a direct or indirect role in the process of monitoring and controlling the physical load of athletes.

Keywords: Football, external load, GPS, inertial sensors, monitoring, training process, injury prevention, sensor data fusion

Introduction

The recent trend in modern football is the growing interest in monitoring physical loads resulting from increased demands on players' endurance and minimized risks for injuries. Technologies such as GPS and inertial sensors enable objective measurement of movement characteristics both during matches and training, hence valuable information regarding external load. This is especially important in high-intensity competitive environments, where heavy physical load can increase the likelihood of injuries, as shown by studies in related sports [1].

External load is understood as the physical volume of work performed, expressed in objective metrics such as distance covered, acceleration, speed, number of sprints, and directional changes, regardless of the player's physiological state [2]. This distinguishes it from internal load, which reflects the body's response, for example, heart rate or subjective fatigue perception. External load characterizes the movement itself and its properties, thus enabling assessment of activity without the influence of individual physiological differences.

The main goal of monitoring physical indicators with GPS and inertial sensors is to provide objective, quantitatively measurable information on which training processes can be optimized, workloads individualized, and injury incidence reduced. GPS captures spatial movement parameters such as distance covered, speed, intensity zones, and heat maps of movement, creating the basis for understanding load in a spatiotemporal context. In contrast, inertial sensors, including accelerometers and gyroscopes, make it possible to detect micro-movements, directional changes, sharp accelerations, and decelerations that GPS may not capture accurately due to limitations in data update frequency and signal conditions.

Thus, a combined approach that includes GPS and IMU provides a more complete picture of external load: GPS delivers spatial and velocity assessment, while IMU records the dynamics and kinematic features of movement. This forms the basis for comprehensive evaluation, contributing to more effective training programs, better recovery, and reduced injury risk in football players.

Materials and Methodology

The study of external load monitoring in football players using GPS and inertial sensors was based on the analysis of 12 sources, including experimental works, reviews, validation studies, methodological guidelines, and reports on the use of these technologies in team sports. Books and articles describing the differences between external and internal load, the operating principle of GPS and IMU, and their integration toward a comprehensive assessment of athletes' movements were included. The paper by Theodoropoulos *et al*. [2] reviews salient areas for the application of tracking systems in football, while studies conducted by Scott MTU *et al*. [3] prove the validity of GPS metrics about linear movements, with reduced accuracy when in high acceleration. Works by Hoppe *et al*. [5] and Pillitteri *et al*. [6] provided practical evidence on the accuracy of measurements in open and indoor environments, respectively, while Wang *et al*. [7] described multi-level data fusion methods that make assessments much more reliable.
The methodological approach embraced three complementary directions. Technical analysis of the GPS and IMU characteristics: Comparison of sampling frequencies, measurement ranges, and methods by which signal filtering is carried out. GPS systems were considered in terms of their ability to record spatial parameters (distance, speed, and heat maps). At the same time, IMU were analyzed in the context of registering linear accelerations, angular velocities, and body orientation. The second direction involved studying installation and calibration protocols, including mounting sensors in a vest between the player's shoulder blades and alternative limb-mounted configurations, as described in the works of Davies *et al*. [4]. The third direction was the analysis of data integration into practice: processing coordinate and acceleration time series, calculating intensity zones, individualized sprint thresholds, and aggregated external load indices, as well as comparing obtained metrics with tactical context and medical indicators, as proposed in studies by Ravé *et al*. [8] and Praça *et al*. [9].

Results and Discussion

The technological base of external load monitoring in football players is founded on two supplementary systems: GPS devices and inertial sensors (IMU). GPS systems work on the basic principle of signal reception from global navigation satellites, where spatial coordinates, speed, and direction of an athlete's movement can be calculated. The measurement frequency has now reached up to 10-15 Hz, thus allowing distance, maximum, and average speed to be recorded as well as intensity zones; besides, heat maps of movement on the field can be generated, thus making a quantitative assessment of external load possible, including variability of load between player positions [3].
Inertial sensors are those that measure linear acceleration, angular velocity, and orientation of the body. IMU can register accelerations and decelerations as well as changes in direction, thereby highlighting movements not captured by GPS due to its low data update rate or when the signals become unstable during fast maneuvers or dynamic crashes [2]. One such sensor is illustrated in Figure 2.

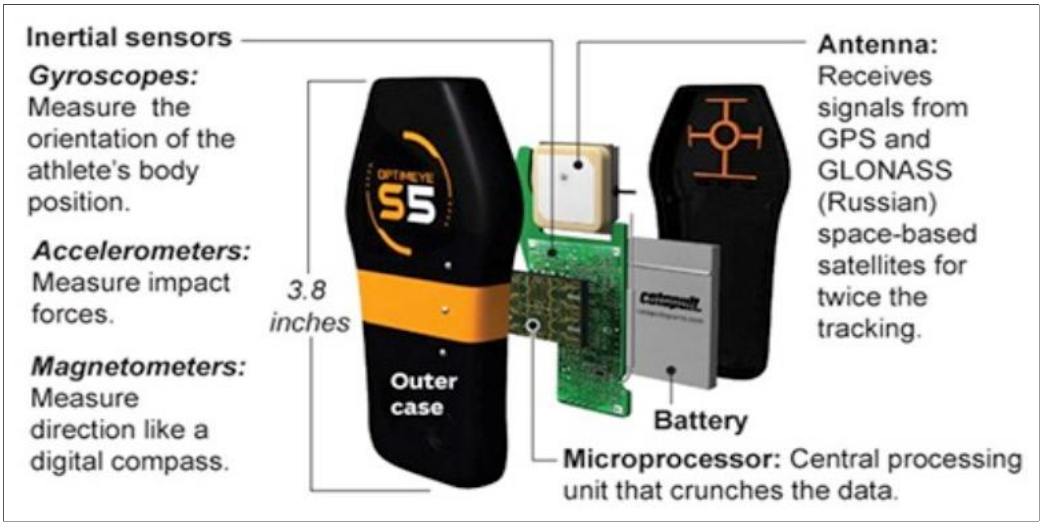

Fig 1: Schematic of Catapult OptimeyeS5 monitor [2]

The combination of GPS and IMU provides more comprehensive tech coverage. GPS info gives where and when moves happen, while IMU shows fine details of how actions take place. GPS/INS tech uses the GPS signal to check the inertial setup periodically, improving spot accuracy and enabling movement modeling if there's a short break in the signal.
The setup of gear for footballers needs to be very careful so that there is no hindrance in their movement, and also does not affect the accuracy of measurement. Mostly, the GPS unit and IMU are to be mounted on a specially designed vest between the blades of the player's shoulders, which ensures stable sensor positioning and also the security of the device. In some studies, IMU are mounted on limbs (e.g., on the shin or footwear), and kicking force assessment, leg rotation, and other specific parameters can be more accurately assessed. Still, a compromise has to be made between comfort and the quality of data obtained [4].
So, the tech side of tracking external load in football is a mixed approach, where GPS tools give location hints, IMU

shares movement details, and the info mix aids coaches and experts to see a clear view of load. This allows for a more exact fit of training, stopping harm, and improving healing speed.

In monitoring external loads, GPS metrics arise from coordinate and speed time series with a typical frequency of around 10–18 Hz, enabling the computation of total distance, speed profiles, sprint count and duration, as well as movement heat maps [5]. The validity of 10 Hz systems has been checked for linear movements. However, precision decreases with increasing acceleration plus abrupt changes in direction; this should be taken into account while interpreting sprints and their peak speeds. These features are confirmed in studies on GPS validity and comparative analysis of sprint thresholds.

Inertial sensors complement GPS by capturing linear accelerations and angular velocities, enabling quantitative assessment of accelerations, decelerations, body orientation changes, jumps, and collisions. In applied practice, aggregated accelerometric indices of external load are used, based on total mechanical activity along the axes. Validation studies for football (Figure 2) show that modern ISD/IMU correctly register locomotion and sport-specific technical elements, maintaining acceptable reproducibility in both indoor and outdoor conditions. A separate area involves timestamping impact and collision events through high peak accelerations, as reflected in reviews on head impacts and in studies with foot-mounted ISD, which detail step, ball-kick, and landing events [6].

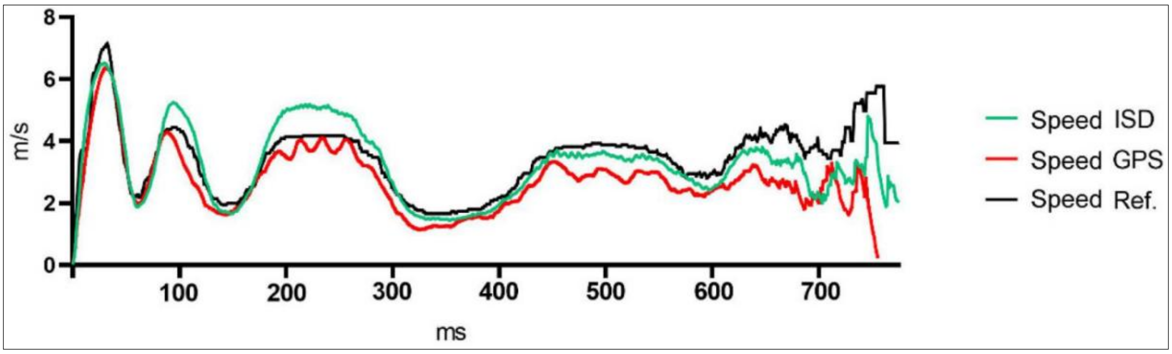

Fig 2: Aggregated data for ISD, GPS, and reference system during soccer-specific circuit [6]

GPS gives information about position relating to distance or speed while IMU enhances this data with minute correction details on short bursts of acceleration as well as deceleration or direction changes (normally where errors in GPS become very pronounced). In sensor fusion methods, the inertial estimate can be calibrated to the satellite data and provide smoothing of trajectories for short-term losses in satellite signals, hence improving both change-of-direction event detection as well as deceleration stress analysis. Multi-level fusion potential, where GPS and IMU data are fused with further available data streams to increase informativeness about holistic external load assessment, has been indicated recently, which is consistent with research regarding the dependency of GPS accuracy on acceleration and studies on team sports fusion algorithms [7].

The volume and spatial distribution, together with the mechanics of high-intensity episodes, perfectly describe movement. This gives a perfect picture of the external load that is later used for individualizing training and managing the overload risk of football players.

The application of GPS and IMU data in the training process relies on the metrics described earlier. It translates them into management decisions for a specific player and the entire team. Individualization begins with profiling speed zones and loads relative to the athlete’s power and speed potential, after which target shares of high-speed work, the number of sprints, and the volume of accelerations and decelerations within microcycles are planned. Practical guidelines recommend rolling windows and also watching the weekly structure of load together with comparison of external load to technical role and minutes played, which minimizes the risk for systematic error and increases reproducibility of on-field decisions [8]. This was a review article about the application of tracking systems in team sports and one methodological material for football, wherein GPS data has already become the foundation for objective load planning as well as manipulation during training.

After-game review joins up volume-energy signs with the tactical setting of moments. Place info lets us work out the team's center of weight, setup length and width, spread area, and sync signs, which help judge how the picked game plan matches the gained motion habits and the sharing of work across lines. The reliability of several tactical variables measured using tracking data has been confirmed: for formation length and width metrics, intraclass correlation coefficients above 0.9 with a standard error of measurement below 10 percent have been reported, making them suitable for regular feedback to the coaching staff and fine-tuning game exercise scenarios in the next microcycle [9]. These findings match what’s usually found in studies about how people use positional metrics to analyze tactics in football.

Prevention of injury and recovery monitoring depends on the early detection of “red flags” in external load and criterion-based on-field rehabilitation management. As indicated by a multi-center study of elite women’s football, the anticipated incidence of time-loss injuries is approximately 35 cases per season per team, with match risk close to four times higher than in training. Therefore, monitoring has to be related to peaks in competitive intensity and the match schedule as indicated in Figure 3 [10].

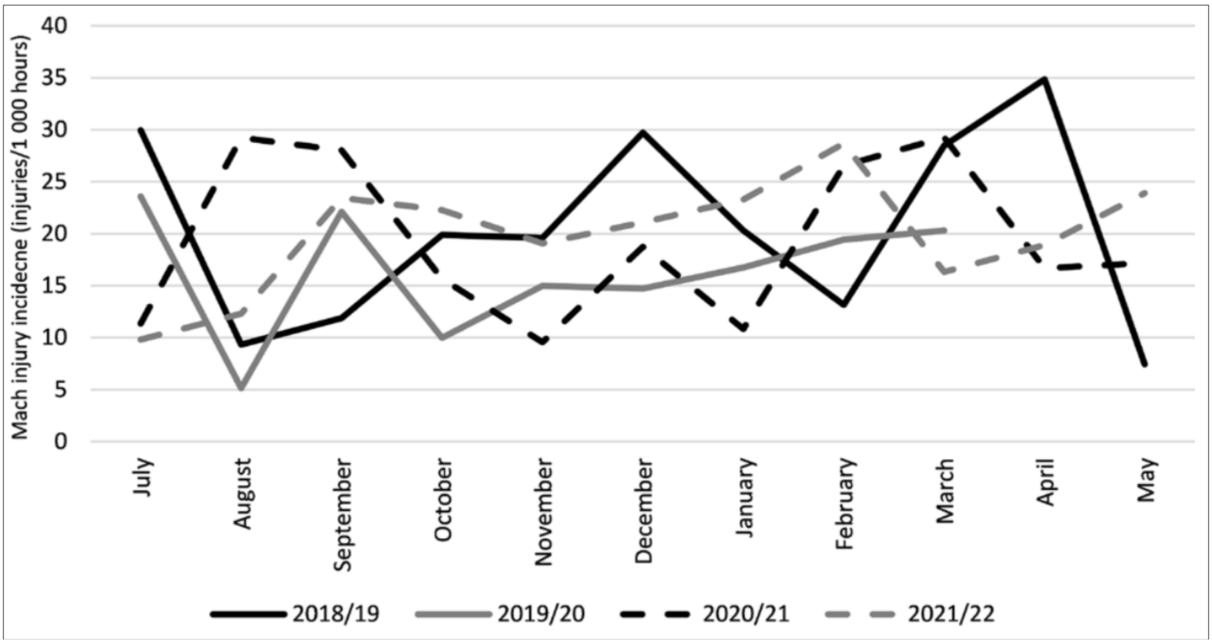

Fig 3: Training and match injury incidences per month during the 2018/2019 to 2021/2022 seasons [10]

Recent workload history is taken as External load spikes because, in the English Premier League study, significant increases in the acute-to-chronic workload ratio were noted to be significantly associated with a probability of sustaining an injury. Lower risk is related to moderate values of this ratio; hence, justification for gradual volume and intensity increase. Running at high speed and sharp decelerations can be well used in the return-to-sport phase, as prescribed by GPS and IMU data, as well as monitoring interlimb asymmetry and load tolerance during on-field exercises. Protocols that are faster on-field and clinically detailed, and reduce return to play time with low recurrence risk, further strengthen any other objective criterion currently in use as a progress tracker during rehabilitation. Long-term tracking permits individual load and recovery profiling for the season-at-field control with accumulated external load indicators plus those sensitivity markers that can pick up changes in the quality of movement, such as IMU-based asymmetry indices, and functional tests [11].

So, a look at the books proves the point of view that monitoring systems with the right judgment do help in comparing outside load, readiness, and output, making it easier to make a fair choice on slow job growth and sharing of roles. League-and club-level show where clear harm trends in multi-year groups point out big metric shifts, training harm rate drops in certain samples, management over time pays off, though care is taken about cause [12]. Within the team, such longitudinal panels help spot steady rises in high-speed work with no jump in sharp slowdowns, seen as a qualitative gain in specific endurance at safe load levels.

Limitations and challenges that might be encountered in the implementation of such systems are based on accuracy under real-world dynamism. Since GPS is highly susceptible to shielding and multipath effects, inside arenas, beneath stands, or near tall structures, the quality of positioning would decrease, which would thus affect distance and speed calculations, and sharp maneuver detections. Inertial sensors suffer from drift and noise, while filtering smoothes out peaks both in acceleration and deceleration; thus, the most intense episodes could even be underestimated. Algorithm performance is also a function of sampling frequency and sync stability between the devices. The final error will be one of the placement accuracy of the sensor on the player's body, especially in repeated measurements. Technical maintenance and calibration belong to the category that requires a systematic approach. Zero-calibration procedures for accelerometers and gyroscopes, regular checks for magnetometric interference, firmware updates, and battery status control. Mount-wearing protocol standardization, maintaining the same sensor position relative to anatomical landmarks, quick connection, and time synchronization test between all devices before session start are also implemented. A data quality audit will be conducted after the session, which includes checking for gaps and amplitude anomalies in clocks and matching with the video and training log.

Financial and organizational hindrances are also huge. The whole list includes a full device fleet, analytical software licenses, cloud storage, consumables that need periodic replacement, and staff training, for just ownership. In the youth and amateur teams, the equipment is shared among quite a few groups; therefore, continuity of longitudinal monitoring is not maintained; logistical losses are found in charging, inventory, and general device maintenance with a busy schedule. Functionality versus reliability versus cost-every choice should be made based on what the priority is, e.g., metrics used by the coaching staff.

Expert judgment and contextual awareness are key to the correct interpretation. External load is not internal load; the same values of metrics can have different physiological costs between players of various fitness levels, playing roles, and injury histories. Speed, acceleration, and sprint thresholds should ideally be individualized and set following technical tasks on the training day, surface type, and weather to avoid false alarms and wrong management decisions. To increase the dependability of conclusions, GPS and inertial sensor data should also be merged with video tracking, where feasible, with medical monitoring data and subjective well-being scales. In addition to the methodological issues, ethical and legal aspects are: player consent for data collection, transparent rules for access and storage of personal information, and results communicated within the staff. This type of holistic approach minimizes error risk and changes the technology from being a provider of numbers to a decision-making tool.

Conclusion

In conclusion, the presented materials confirm that the combined use of GPS and inertial sensors provides an objective and multifaceted assessment of external load in football players. GPS delivers spatiotemporal movement characteristics such as distance covered, speed profiles, intensity zones, and heat maps of movement, whereas IMU records microdynamics: accelerations, decelerations, changes of direction, jumps, and collision events. Data streams make up the holistic view of the work performed, thus creating the background against which the training process can be optimized, individual workload individualized, and injury incidence reduced. Measurement accuracy features set boundaries for interpretation. Metric validity for linear movements is higher with GPS; accuracy drops as accelerations increase and with abrupt changes of direction, thus caution needs to be considered when analyzing sprints and peak speeds. Speed threshold zones are arbitrary, though individualized thresholds seem to be more valid than absolute thresholds, which do not appear to be universally less valid. Inertial sensors correctly identify both the locomotion and technical elements particular to sports and permit aggregation of mechanical activity through accelerometric indices when impact events are identified. They suffer from drift, as well as from the quality of signal filtering. In sensor fusion approaches wherein GPS calibrates inertial estimates besides stabilizing trajectories during temporary signal loss periods, metric reliability is improved, particularly over short high-intensity episodes.

The practical value of comprehensive monitoring is manifested at three levels. At the training level, speed metrics, number of sprints, and acceleration and deceleration volumes are planned and controlled within microcycles, taking into account player role and playing time. At the tactical level, positional data permits assessment of formation length and width, stretch area, and synchronization indicators, making regular and reproducible feedback to coaching staff possible, including fine-tuning of game exercise scenarios. At the medical-rehabilitation stage, monitoring can assist with early detection of adverse workload spikes, comparison between acute and chronic work, as well as dosing high-speed segments and deceleration stress during return to sport, as well as asymmetry and load tolerance on the field.

Technologies such as these require organizational and technical prerequisites. GPS is sensitive to matters of shielding and multipath, the sensitivity of the sampling frequency, and synchronization of the devices. Stable and repeatable sensor attachment has proved critical in practice. Regular calibration plus standardization of wearing and maintenance, data quality audits, and comparison with video tracking and training logs enhance the reliability of conclusions.The financial injection for device fleets, software, and staff training is massive; thus, this factor becomes imperative in the decision-making process. Ethical considerations are informed consent, transparent rules of data access and protection, as well as accurate result communication within the staff.

If data collection and quality control are up to best practices, GPS & IMU technologies can be considered as an achievable, valid external load management foundation. When comprehensively interpreted together with other sources of information like video tracking, medical indicators, and subjective well-being scales, raw signals may be turned into justified tools for training planning and tactical feedback, in addition to safe return-to-play protocols. These applications work best when individualizing thresholds for the user and understanding the context in which the metrics are being utilized.

Due to their measurement limitations and the context in which they are being calculated, systematic caution must be applied in using these metrics in making decisions at both the team level and for specific tasks regarding players.

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Conflict of interest

All authors declare the absence of any conflict of interest, financial or otherwise, in connection with the content of the manuscript, the products mentioned therein, and their competitors.

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