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Design Requirements of a Novel Wearable System for Safety and Performance Monitoring in Women's Soccer

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Featured Application

A wearable system design for monitoring of professional and amateur female soccer players dedicated to improve safety (specifically for head impacts) and performance assessment.

Abstract

Female soccer is rapidly becoming a widely practiced sport at different levels: this opens up a new demand for systems meant to protect athletes from head impacts or to monitor their effects. The market is offering some solutions in similar sports, but the specificity and high relevance of soccer encourage the development of a dedicated solution. From market analysis, technology scouting, and ethnographic research a set of functional and technical requirements have been defined and proposed. The designed instrumented head band is equipped with one Inertial Measurement Unit (IMU) in the occipital area and four contact pressure sensors on the sides. The concept design is low-cost and open-architecture, prioritizing accessibility over complexity. The modularity also ensures that each component (sensing, battery, communication) can be replaced or upgraded independently, enabling iterative refinement and integration into future sports safety systems. In addition to safety monitoring for injury prevention or detection of the traumatic impact, the system is relevant for supporting performance monitoring, rehabilitation or post-injury recovery and other important applications. System engineering has started and the next step is building the prototypes for testing and validation.

Keywords: wearable sensor; female soccer; injury prevention; performance monitoring

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1. Introduction

Traumatic brain injuries (TBIs), particularly concussions, represent a significant medical concern in contact sports nowadays [1] with potential long term consequences, such as cognitive decline and neurodegeneration [2,3]. In the United States alone, the Centers for Disease Control and Prevention (CDC) estimates that between 1.6 and 3.8 million people experience a sport-related TBI every year [4]. Within this broader context, women's soccer represents a sport-specific and increasingly relevant scenario. Soccer is one of the most widely practiced sports worldwide, and women's participation has grown rapidly at professional, semi-professional, and youth levels [5,6].

Several studies reported that when accounting for soccer exposure, women have a higher injury risk than men [5,7–11]. Specifically, female soccer players sustain concussions at a rate that is 1.76 times higher than that of their male counterparts [12]. Behind these results there are different speculative explanations that mainly concern biomechanical and anatomical factors: female subjects exhibit smaller head-to-ball ratios and weaker neck muscles [13,14], as well as less head/neck mass than male subjects. Furthermore, higher angular acceleration of the neck and head is also observed [7].

Concussions, from a biomechanical perspective, are caused by the transfer of energy to the brain tissue [15]. The brain has unique physical properties—such as high bulk modulus, low shear modulus, and suspension in cerebrospinal fluid—which make it particularly sensitive [16,17]. Therefore, rotational loading is especially damaging, contributing to the rise in the diffuse axonal injury (DAI), which is the characteristic lesion of TBI [18,19]. Diagnosis of TBI, particularly in sport, remains complex. Traditionally, the recognition relies on clinical judgment and athlete self-reporting, both of which are vulnerable to subjectivity and underreporting [20,21]. It has been reported that less than half of athletes who suffer a sports-related concussion report their injury, often because they underestimate the severity of the injury or fear being removed from the game [20]. Traditional methods, such as self-reporting [20,22] or observer-based assessments [23], are particularly subject to error, leading to delays in management and increasing the risk of athletes returning to play while still injured [24].

The introduction of wearable sensor technology allows real-time monitoring and advanced objectives [25] that overcome the limitations of subjective and delayed assessments. Wearable sensors typically include a triaxial accelerometer and gyroscope that allow both linear and rotational kinematics to be recorded, bringing a comprehensive overview of the head dynamics during the impact [26,27]. Using this technology—called Inertial Measurement Unit (IMU)—when integrated in a single device or chip, is not intended to diagnose concussions—which remain a clinical judgment—but to detect potential injuries that might otherwise go unnoticed.

A variety of technologies have been developed, including helmet-integrated sensors, skin-mounted patches, headbands, and instrumented mouthguards [28]. Mouthguards offer a rigid coupling to the skull and thus higher measurement accuracy [29,30]. However, they are less adopted in sports such as soccer, where mouthguard adoption is not common. Moreover, helmet-based solutions cannot be directly transferred to non-helmeted sports.

Currently, most head-impact monitor systems are developed for professional-level collision sports; consequently, there is a lack of affordable, non-invasive solutions designed for the specific dynamics of non-helmeted sports [31] like women's soccer, where athlete compliance and ease of use are primary barriers to adoption [32]. This study aims to establish a preliminary technical and theoretical framework for a sport-specific monitoring system. The novelty of the proposed research lies in the integration of an ethnographic video analysis with a technical benchmark to define a sport-specific design framework. This exploratory approach focuses on identifying the necessary sensor topology and performance requirements, translating market and field findings into a conceptual design proposal by addressing the specific biomechanical and compliance needs of female athletes.

2. Materials and Methods

To investigate the current state of the art, and to define the needs and design requirements, a deep analysis of the scientific literature available on the topic, and of the available market solutions in similar applications, was conducted.

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2.1. Benchmark and Literature Review

A comparative analysis of existing technologies and monitoring standards was conducted in order to define the frameworks' design requirements. This benchmark serves to identify the standards used for other disciplines that can be adapted to the specific constraints of women's soccer.

Head Impact Kinematics and Concussion Protocols Across Sports

The analysis of kinematics and protocols in established contact sports serves to define the system's technical requirements. Peak accelerations and impact direction provides a benchmark for sensor selection, specifically for dynamic range and sampling frequency. This ensures that the proposed framework for women's soccer is calibrated against established performance standards and existing data management protocols.

Soccer is unique among contact sports because head-to-ball contact is intentional and part of the game. During matches and training, players experience repeated head impacts from contact with the ball, adversaries, or the ground. Even though the majority of these are sub-concussive, concerns have been expressed concerning the cumulative effect of repetitive sub-concussive head impacts (RSHIs) and about possible long-term neurological effects [33].

To quantify soccer head impacts, instrumented mouthguards and other accelerometer-based systems have been used. Observational studies report mean pLA between 3 and 45 g, with corresponding pRA reaching up to ~7000 rad/s^2 [33]. Ball-to-head impacts commonly generate values of peak linear acceleration (pLA) in the range of 10–20 g. In contrast, non-ball-related incidents, such as head contact with head or elbow, or falling, may be associated with higher accelerations of two to five times the values in the above range, occasionally reaching above 80 g [34,35]. The Fédération Internationale de Football Association (FIFA) and the national football federations have taken special care in addressing issues of concussion diagnosis and management, as well as methods of prevention. Several associations have introduced age-specific guidelines to mitigate potential long-term risks.

Detailed descriptive analysis of head impact kinematics and protocols for American Football, Rugby, Taekwondo, Boking and Ice Hockey is provided in Appendix A. These data serve as the technical basis for the comparative synthesis presented in Table 1.

Table 1. Typologies of impacts and acceleration peaks in different sports.

Sport	Typical Impact Direction	Peak Linear Acceleration (g)	Peak Rotational Acceleration (rad/s^2)
Soccer	Ball-to-head contact (frontal); higher forces in head-to-head, elbow, or ground impacts	Typically 3–45 g; up to >80 g in non-ball impacts	Up to ~7000 rad/s^2
American Football	Frontal blows, lateral/posterior	11.2–82.7 g (mean 31.7 ± 17.7 g)	495–5205 rad/s^2 (mean 2072 ± 112 rad/s^2)
Rugby	Mixed; mostly player collisions	Rugby Union: Mean 17.35 g (95% CI: 14.68–20.02 g) Rugby League: Mean 25.19 g (95% CI: 7.64–42.73 g)	Mean 1259.51 rad/s^2 (95% CI: 1112.12–1406.91 rad/s^2)
Boxing	Face, chin, jaw (frontal/lateral)	71.23 ± 32.19 g	9306 ± 4485 rad/s^2
Taekwondo	Chin, side, top (punches and kicks)	130.11 ± 51.67 g	10,927 ± 8017 rad/s^2
Ice Hockey	Back of head (boards/falls) > frontal/side/top impacts	41.6 g (95% CI: 36.6–49.5)	4424 rad/s^2 (95% CI: 4076–5182)

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2.2. Market Analysis of Wearable Technologies for Monitoring Head Impact in Contact Sports

To evaluate the current state of the art, a market analysis was conducted on wearable systems developed over the past two decades for monitoring head kinematics. Although these systems are not diagnostic tools, they provide objective, real-time measurements of impact intensity, typically through the integration triaxial accelerometers and gyroscopes [36].

The analysis focuses on four major categories of sensors, depending on the coupling technology, namely: (i) helmet-integrated sensors, (ii) instrumented mouthguards, (iii) headbands/skull caps, and (iv) skin-mounted patches. Only systems that are either commercially available on the market or thoroughly described in the scientific literature, for which technical details and scientific validation data are available, were considered. The detailed examination of existing parameters represents a specific benchmark. By cross-referencing the accuracy and technical constraints of each category, the objective was to identify the optimal technical positioning for a new framework tailored to the specific ergonomic and impact-profile requirements of women's soccer.

- Helmet-Integrated Sensors

By embedding IMUs within the helmet liner or shell, they achieve stable mounting, continuous power supply and team-wide deployment.

HIT System—The Head Impact Telemetry System (HITS), developed by Simbex LLC (Lebanon, NH, USA) in the early 2000s, was the first commercially feasible helmet-integrated system designed for the real-time monitoring of head impacts. This system calculates a composite measure of head impact exposure (HIE), which evaluates the frequency and severity of impacts an athlete experiences, using a network of accelerometers (usually six sensors) integrated into the helmet lining. Coaches and medical staff are notified if impact exceeds a predefined HIE threshold by wirelessly sending the data to a receiver on the sidelines. HITS was first integrated into Riddell Inc (Des Plaines, IL, USA) football helmets as a part of the InSite Analytics platform. Today, it is a crucial part of the standard technology package in the Riddell Axiom helmet line. Simbex (Lebanon, NH) developed analytical databases for extensive monitoring of athlete exposures. Since then, HITS has been implemented across youth, collegiate, and professional football, producing some of the most comprehensive epidemiological datasets concerning head impacts in sports [37].

NoMo Diagnostics—The NoMo Diagnostics project at Columbia University involves the integration of miniaturized electroencephalogram (EEG) sensors between the padding layers of a football helmet, with the objective of ensuring direct contact between the electrodes and the scalp. When an athlete is hit, the system analyses the brain's electrical activity in real time, looking for abnormal patterns characteristic of concussion and transmits an alert to the sideline computer within seconds. Unlike the accelerometer-based systems, which detect concussion impact magnitude, NoMo recognizes a direct physiological signature of brain injury by monitoring changes in neural activity triggered by trauma. Preliminary tests conducted with Columbia University players have demonstrated the feasibility of recording brainwaves during practice, although there is still the need for further miniaturization to improve comfort and reduce motion artifacts [38].

Smart skiing and cycling helmets: In recent years, there has been a notable proliferation of commercially available helmets that incorporate sensors as an integral component of their design. These sensors are strategically positioned within the helmet's shell, with the primary objective being to enhance user safety, particularly in activities such as skiing and cycling, where individuals participate in these activities independently.

Atomic Skis (Salzburg, Austria)'s CTD (Crash Tech Development) helmets incorporate the Shocksense module, which combines an embedded impact sensor (accelerometer) with

GPS to detect significant falls and automatically trigger emergency protocols. The transmission of data to the designated Atomic Shocksense smartphone application is initiated, thereby facilitating the storage of impact history, the monitoring of helmet condition, and the transmission of SOS alerts in the event of high-energy impacts. This system is most valuable to individual winter sports, where rapid crash detection and location reporting enhance safety. However, the technology is designed primarily for emergency response and helmet-integrity monitoring rather than detailed biomechanical measurement, and thus provides limited utility for precise head-kinematics assessment, especially rotational dynamics, needed for concussion risk evaluation [39].

Livall Tech Co. (Zhuhai, China) Smart Helmets apply a similar concept to cycling applications. This system incorporates embedded motion sensors (accelerometers, and in some models multi-axis IMUs) to detect crashes and sudden decelerations. The helmets communicate via Bluetooth with the Livall smartphone app, which manages SOS alerts, GPS-based location sharing, and emergency contact notifications. In addition to crash detection, the Livall helmets offer integrated lighting and audio functions aimed at enhancing rider visibility [40].

The reliance on helmet dynamics can compromise the precision of helmet-based measurement systems, particularly in the context of quantifying true head kinematics, such as rotational acceleration, when compared to skull-coupled devices, such as instrumented mouthguards. Consequently, helmet sensors are best regarded as a complementary modality: their strengths lie in exposure surveillance and crash alerts in helmeted disciplines, yet they frequently fall short when it comes to precise biomechanical input necessary for concussion risk modeling.

- Smart Mouthguards

Instrumented or smart mouthguards are among the most advanced and widely adopted solutions for monitoring head impacts. The rationale is that a mouthguard tightly fitted to the teeth is rigidly coupled to the skull, allowing accurate measurement of head acceleration. Several studies have shown that this position provides more reliable data than sensors mounted on helmets or skin, reducing errors due to relative motion [41].

In recent years, various companies and research centers have introduced commercially, or experimentally available mouthguards equipped with IMUs to record linear and rotational head accelerations during impacts. Some models also include additional sensors, such as optical heart rate sensors or magnetometers, to expand the range of measured parameters [42].

Prevent Biometrics (Edina, MN, USA): A scientifically validated smart mouthguard has been developed in collaboration with the Cleveland Clinic. The mouthguard integrates a high-fidelity IMU (tri-axial linear accelerometer and a gyroscope) (sampling rate: 3.2 kHz; linear measurement range: $\pm$200 g; angular measurement range: $\pm$34.9 rad/s [42]) [43] within a custom-fit mouthguard and a boil-and-bite one. It allows for the measurement of both linear and angular acceleration, and the calculation of biomechanical trauma indicators (e.g., brain injury criteria). In laboratories and field studies, it has shown high accuracy: G. Tierney, (2024) defined it as the highest performing mouthguard, with a concordance correlation coefficient (CCC) value of 0.97 across the measurements and a mean relative error in the peak of the magnitude of <5% for angular acceleration, angular velocity and linear acceleration at the test dummy head center of gravity [41,44]. Prevent uses an algorithm to filter out measurements suspected to be associated with non-impact events. The mouthguard sends data via Bluetooth to the Prevent Biometrics app. Each device has a unique serial number, and proper assignment ensures this data is linked to the correct player. When an injury happens, an alert is sent to the medical staff as soon as an impact exceeds a preset threshold and this allows immediate identification of players. The device is designed for professional use: it includes a UV sanitizing and charging dock for individual or team mouthguards and a cloud portal for detailed data analysis [45].

HitIQ (Melbourne, Australia): A custom-fit mouthguard created with dental impression [46]. It integrates a tri-axial accelerometer (Analog Devices (Wilmington, MN, USA) ADXL372, range: ±200 G, 12-bit) and a gyroscope (Robert Bosch GmbH (Gerlingen, Germany) BMG 250, ±2000 dps range, 16-bit) sampled at 3.2 kHz and 0.8 kHz, respectively. The three-accelerometer array are located in the left, central, and right regions of the mouthguard to provide an estimate of the angular acceleration independent of the gyroscope and allowing for the removal of spurious readings, such as those originating from actions like mouthguard deformation rather than head kinematics. The gyroscope is positioned on the inside of the central incisors [47]. The mouthguard embeds the circuit board and components such as a battery and antenna system [48]. Data on linear and rotational acceleration peaks are sent in real-time via Bluetooth 5.0 to a mobile app, providing immediate alerts. It is specifically designed to make advanced monitoring technology accessible to community-level rugby, amateur leagues, and youth football. In-lab validation studies found a total concordance correlation coefficient (CCC) of 0.965, similar to that of other high-performance mouthguards. The average bias for peak linear acceleration was −4.0% and for peak angular acceleration it was 4.2% [42]. The device is designed for community-level rugby and football, aiming to make this technology accessible to amateurs [49].

PROTECHT: This smart mouthguard is a collaboration between mouthguard manufacturer OPRO (Hertfordshire, UK) and the Sport and WellBeing Analytics (SWA) (Swansea, Wales, GB) company. The SWA company is responsible for supplying and coating the electronics architecture and firmware within the protection system [50]. The smart mouthguard, named PROTECHT, embeds a tri-axial accelerometer (H3LIS331DL, STMicroelectronics, Genova, Switzerland) and a tri-axial gyroscope (LSM9DS1, STMicroelectronics, Genova, Switzerland) sampled at 1 kHz (±400 g, 12-bit resolution) and 1 kHz (±35 rad/s, 12-bit resolution), respectively [51,52]. It measures linear and rotational accelerations, transmitting the data via Bluetooth connection in real-time to sideline receiver connected to analytics software for monitoring. Its primary users are professional rugby clubs and academies in the UK.

ORB Smart mouthguard: Launched in 2023 by the UK start–up ORB Innovations, the ORB Sport™ (London, GB) Smart Mouthguard is a next-generation intraoral device that combines safety and performance monitoring in a single platform [53]. It integrates a full IMU with a Photoplethysmography (PPG) optical heart-rate sensor. The inertial sensors sample at 1.6 kHz, with a linear measurement range of ±200 g and an angular measurement range of ±34.9 rad/s [42]. The PPG sensor tracks real-time heart rate, calories burned, steps and distance. The transmission of data to the ORB Sport application is facilitated by Bluetooth 5.0, enabling athletes to access real-time heart rate, exercise intensity, session duration, and recorded impact history. Full data access requires a subscription to the associated cloud service. The device targets advanced amateurs and semi-pro athletes in sports like boxing and Mixed Martial Arts, with a consumer-oriented model of a one-time kit purchase plus a monthly data subscription.

Vector Mouthguard (Athlete Intelligence, Kirkland, WA, USA): Developed by Athlete Intelligence (WA, USA), the Vector Smart Mouthguard is a field-tested device designed for high school, collegiate, and amateur contact sports such as football, hockey, and rugby. It includes a three-axis accelerometer (sampling at 1.024 kHz, ±200 g) and a three-axis gyroscope (sampling at 0.76 kHz, ±35 rad/s) to measure both the magnitude and location of head impacts [54]. The data are transmitted in real-time via a 915 MHz radio link to a sideline receiver, enabling instant alerts to coaches when an athlete sustains a high-magnitude impact [55]. The scientific validation has shown good reliability: in-laboratory tests by Kieffer et al. (2020) reported a concordance correlation coefficient (CCC) of 0.94 for pLA and 0.61 for pRA, yielding an overall CCC of 0.80 [43]. On-field testing also reached an overall CCC near 0.80, indicating consistent performance in real playing conditions. The Vector is primarily offered as part of team packages, which include the mouthguards and cloud-based analytics software for large-scale monitoring.

In summary, instrumented mouthguards currently represent the state of the art in monitoring cranial impacts: they provide objective measurements of the brain's accelerations during every contact. Differences exist in usage modes (real-time vs. post-game), in the inclusion of additional sensors (e.g., heart rate in ORB), in ergonomics (boil-and-bite like Vector vs. custom-fit from dental scans like HitIQ), and in commercial models (consumer retail with app vs. enterprise solutions for teams). Scientific validation of these mouthguards is generally positive.

- Headbands/skull caps

This category of technology includes elastic headbands, skullcaps, and clip-on sensors worn on the head or attached to a helmet. These devices work well in both helmeted sports (attached to the shell) and non-helmeted sports (worn as bands around the head or under standard headgear).

CUE+ Sport Sensor (Athlete Intelligence, WA, USA): The CUE+ Sport Sensor, developed by Athlete Intelligence, was created as an alternative head-impact monitor for athletes who do not (or cannot) use instrumented mouthguards. It is a small rectangular module that can be affixed to helmets in sports such as football, lacrosse, and hockey, or worn on headbands for non-helmeted sports such as lacrosse, soccer, and field hockey. The device integrates a tri-axial accelerometer and a low-power IMU comprising a separate tri-axial accelerometer and tri-axial gyroscope, sampling at 1.6 kHz [56]. The newer CUE+ version also incorporates a thermometer to monitor body temperature, providing early warning of potential heat stress in addition to impact exposure. In-laboratory validation showed limited accuracy compared to instrumented mouthguards, with a concordance correlation coefficient (CCC) of 0.43 for pLA and −0.04 for pRA, yielding a combined CCC of 0.13 for both kinematic measures [43]. In the base CUE model, data are stored locally and uploaded via Bluetooth 5.0 to the dedicated app at the end of a session, whereas the CUE+ version transmits data in real time via a 915 MHz radio link to a sideline receiver, allowing staff to receive instant alerts [55].

In addition to devices integrated into headbands, skull caps, or closely worn headgear, there are a number of clip- or strap-on sensors, such as the HIT Concussion, Tocsen, ICEdot, Jolt Sensor, G-Force Tracker, etc., that have been used in the past or are still used in certain contexts for head impact or crash/fall detection. These devices tend to be more accessible and lower-cost, designing the use mainly for recreational activities, or emergency alerting rather than precise biomechanical monitoring. However, many of them are now either discontinued, have limited or inconsistent publicly available technical specifications (sampling rates, accelerometer vs. gyroscope inclusion, transmission), or lack recent peer-reviewed validation. Because of these uncertainties, their data are often not accepted in research studies with high precision demands.

- Skin-mounted patches

An alternative to the previously presented solutions is the use of adhesive sensors placed on the skin, typically near the skull (behind the ear, on the nape, or forehead). These electronic patches allow head motion monitoring without requiring the use of helmet, headbands or mouthguard with a more discrete aspect. The most well-known device in this category is the X-Patch introduced in the early 2010s by X2 Biosystem (Seattle, WA, USA). It is a small button-shaped adhesive device applied with a patch behind the ear typically placed at the right mastoid process [43,57,58]. The sensor contains a triaxial accelerometer (sampling at 1 kHz) and a gyroscope (sampling at 850 Hz) that together record six degrees of freedom of head kinematics [43]. It also calculates the head impact location, Head Injury Criterion (HIC), and Gadd Severity Index (GSI) and derives rotational velocity. Impact identification is performed using the X2 Biosystems' proprietary algorithm [59]. The data are stored within the device and can be downloaded post-event to a PC or sent in real time to a mobile device.

In laboratory validation studies, Kieffer et al. (2020) reported a combined concordance correlation coefficient (CCC) of 0.83 for pLA and pRA in helmeted tests, and 0.70 in non-helmeted tests [43]. The X-Patch system has several key limitations, including device malfunctions (such as battery drainage and time-stamp corruption) [57], variable accuracy of linear and angular acceleration measurements under different conditions, and susceptibility to dermal artifact from imperfect skin-to-sensor coupling [30,60]. Additionally, its proprietary impact-filtering algorithm may misclassify events, leading to potential false positives or negatives and affecting both impact counts and magnitude estimates [59,61,62].

Based on the X-Patch, improved variants emerged. Other companies proposed similar sensors: for instance, Prevent Biometrics initially tested a patch (later focusing on mouthguards), and BrainScope (Bethesda, MA, USA) offered a frontal patch for EEG purposes. In Australian rugby and football, some studies used inertial patches applied to the mastoid to assess impact exposure. However, many of these accelerometer patches share limited attachment stability.

To provide a comprehensive synthesis of the state of the art, existing technologies are benchmarked against both technical specifications and functional requirements for soccer. Table 2 provides a detailed breakdown of the identified devices cross-referencing hardware capabilities with scientific validation metrics and ergonomic constraints. To facilitate a comparison between the different coupling strategies, these findings are further synthesized in Table 3, highlighting the performance benchmarks, cost ranges, and the primary technological gaps that the proposed framework intends to address.

Table 2. Detailed technical and functional benchmarking of existing head impact monitoring solutions. Devices are benchmarked across sensor specifications, validation metrics (CCC), target costs, and specific applicability constraints for women's soccer.

Name (Type)	Sensors	Parameters	Placement	Status/Validation	Target and Cost	Limitations and Soccer Applicability
Prevent Biometrics (Mouthguard)	6-axis IMU (3-acc + 3-gyro); 2.4 GHz transmitter	Linear/rot. accel. (g; rad/s^2); impact count; HIA thresholds	Custom-fit mouthguard	Validated (Cleveland Clinic); **CCC: 0.97**; used in World Rugby	Professional teams, research; high cost (team bundles)	Invasive; excellent data but affects breathing/speech in soccer.
HitIQ (Mouthguard)	6-axis IMU; Bluetooth 5.0	Linear/rotational accelerations; real-time transmission	Custom-fit mouthguard	Lab-tested (HitIQ Nexus); **CCC: 0.965**; launched to consumer market	Community rugby, advanced amateurs; mid-high price	Requires dental impression; limited compliance in amateur soccer.
OPRO+ PROTECHT (Mouthguard)	6-axis IMU; proprietary wireless	Linear/rotational accelerations; impact load dashboard	Customizable mouthguard	Used in Pro14/Premiership clubs; validated in UK studies	Professional clubs; provided as a service (subscription pricing)	Professional infrastructure required; high management overhead.
SISU Sense (Mouthguard)	3-axis accelerometer; low-power wireless chip	Events above threshold (e.g., >10 g); impact history via app	Moldable mouthguard	Non-diagnostic tool; 1 season without recharge	Youth athletes, schools; expected low cost	No gyroscope (no rotational data); low utility for concussion risk.
ORB Smart MG (Mouthguard)	3-axis + High-G accelerometer; gyroscope; magnetometer; optical HR sensor; Bluetooth 5	Linear/rotational accelerations; heart rate; steps, distance; calories; impact force and location	Custom-fit mouthguard	Launched in 2024; strong specifications; under early user evaluation	Advanced amateurs/high-end; $349 + subscription	Multi-sensor complexity; battery life constraints.
Vector (Mouthguard)	6-axis IMU; 915 MHz radio; 1.024 kHz	Linear/rotational accelerations; impact location; immediate alert; logs 1000 events	Boil-and-bite mouthguard	Validated (Virginia Tech); Overall **CCC: 0.80**; used in NCAA and high school studies	Contact sport teams (football, rugby, hockey); pricing on request (team solution)	Lower rotational accuracy (**CCC: 0.61**); bulky for soccer headers.
X-Patch (Skin Patch)	6-axis IMU; Bluetooth (Pro models); 1 kHz	Linear/rotational head accelerations; impact count; approximate impact axis	Patch behind ear	Extensive literature (taekwondo, hockey); **CCC: 0.70–0.83**	Research, field tests; less used commercially now	Dermal artifact: sweat causes detachment during play.

Table 2. *Cont.*

Name (Type)	Sensors	Parameters	Placement	Status/Validation	Target and Cost	Limitations and Soccer Applicability
CUE/CUE+ (Clip/Headband)	6-axis IMU; (CUE+: +temp); 915 MHz radio (CUE+: live transmission); 1.6 kHz	Linear/rotational accelerations; impact count and severity; location; workload; body temperature	Clip inside helmet or elastic band	Validated alongside Vector; adopted in HS football programs; Overall **CCC: 0.13**	Mixed teams (helmeted/non); team packages on request	Very low accuracy due to soft tissue motion; ideal form factor but unreliable.
HIT Device (Clip/Headband)	6-axis IMU; GPS; Bluetooth	Impact threshold alarm; GPS crash location; 12–24 h impact logging; waterproof	Transferable unit (helmet or headband)	Tested by professional rugby players; new UK market entrant	Various consumers (outdoor/contact sports); ~$160 per unit	Low-cost entry; absent technical validation for soccer.
Riddell InSite (Helmet-integrated)	Multiple accelerometers in helmet; dedicated radio	Multi-point linear accelerations; alert if impact > preset helmet profile threshold	Integrated into football helmet (e.g., Riddell models)	Based on HIT system; widely used in US high schools	High school/college football; medium cost (premium helmet ~$400–500)	Not applicable to soccer (helmet dependent).
Atomic Shocksense (Ski Helmet)	3-axis accelerometer; Bluetooth; crash SOS sensor	Helmet impact detection; crash SOS trigger; helmet impact history tracking	Integrated into ski helmet	Launched in 2021; Android/iOS app supported	Amateur/professional skiers; (~$350)	Emergency focus; limited biomechanical/rotational data.
NoMo EEG (Prototype Helmet)	EEG electrodes; (additional IMUs for sync)	Brainwaves (EEG); immediate concussion pattern detection	Electrodes embedded in football helmet padding	Preliminary tests (Columbia University); EEG recorded in helmet; miniaturization ongoing	Research; potential NCAA/NFL future adoption	High technical complexity; requires helmet coupling.

Table 3. Synthesis of technical specifications and performance gaps across existing wearable technology categories. A comparative summary highlighting the trade-offs between kinematic accuracy (CCC), ergonomic feasibility, and cost for non-helmeted sports applications.

Technology Category	Dynamic Range (Typically)	Sampling Frequency (Typically)	Accuracy (Avg. CCC)	Ergonomics (Soccer)	Estimated Cost (Unit)	Primary Design Gap
Mouthguards	±150–200 g	1000–3200 Hz	High Fidelity (0.80–0.97)	Low (Invasive)	High cost/Elite ($250–$500+)	High cost and interference with headers/speech.
Headbands	±100–160 g	400–1600 Hz	Low Fidelity (<0.45)	High (Optimal)	Medium Cost ($100–$200)	Low fidelity; lack of stable coupling.

Table 3. *Cont.*

Technology Category	Dynamic Range (Typically)	Sampling Frequency (Typically)	Accuracy (Avg. CCC)	Ergonomics (Soccer)	Estimated Cost (Unit)	Primary Design Gap
Skin Patches	±160–200 g	850–1000 Hz	Medium Fidelity (0.70–0.80)	Medium	Medium Cost ($150–$250)	Attachment issues (sweat/contact) during play.
Helmets	±150–200 g	1000 Hz	N/A	Bulky	High Cost ($300–$600)	Incompatible with soccer regulations.

N/A: Not available.

2.3. Ethnographic Video Analysis and Impact Mapping

To define the optimal sensor topology and component placement, an indirect ethnographic analysis was conducted. While ethnography is traditionally a qualitative method used in social sciences to observe behavior in natural settings [63], in this study, it was adapted to perform a biomechanical task analysis of female soccer matches. Three full-length elite women's soccer matches were selected from available high-definition broadcast footage [64–66]. The analysis aimed to identify the cranial regions most frequently subjected to external forces (ball-to-head or player-to-player contact) and, conversely, to locate safe zones with minimal impact exposure suitable for housing rigid electronic components. Accordingly, the observational data were utilized strictly to identify specific design constraints and ergonomic boundary conditions for hardware development. To ensure data robustness, a double-verification procedure was implemented. A single researcher performed the initial coding, while a second senior researcher reviewed the dataset to validate impact identification and localization. In cases of discordance, a joint assessment was performed.

2.3.1. Data Collection and Zonal Classification

The video footage was analyzed frame-by-frame during high-intensity events. Each detected head impact was logged and spatially mapped onto a 3D head model. To ensure classification consistency and accuracy, the cranium was divided into four macro-zones based on visible anatomical landmarks:

- Frontal Zone: Defined as the region anterior to the coronal plane (forehead), typically involved in intentional heading.
- Parietal Zone: Defined as the superior region of the cranium (crown), extending from the hairline to the lambda.
- Temporal/Lateral Zone: Defined as the lateral aspect of the skull, inferior to the temporal line (side of the head/ears).
- Occipital Zone: Defined as the posterior region of the skull, extending from the lambda to the nuchal lines (back of the head).

2.3.2. Reliability of Classification

To mitigate the subjectivity inherent in 2D video analysis, a conservative classification protocol was adopted. Only impacts where the contact point was clearly visible and unambiguous were included in the dataset. Glancing blows or events where the impact location was obscured by players' bodies were categorized as "unclear" and excluded from the spatial mapping to prevent artifacts in the design requirements.

2.4. Definition of Framework Requirements and Design Criteria

Despite significant progress, existing technologies for monitoring head impacts still present limitations that hinder their widespread adoption in non-helmeted sports, particularly in women's soccer. This section synthesizes the identified market and literature gaps to define the theoretical boundary condition necessary for the proposed framework. These criteria are prioritized to address the specific accuracy and accessibility trade-off identified in the comparative analysis.

- Data accuracy and Reliability

As detailed in the comparative analysis, accuracy varies significantly across device categories. While intraoral devices achieve high fidelity with CCC values exceeding 0.96 [41,42,44], their performance is not universal, as seen with the Vector mouthguard's lower rotational accuracy (pRA CCC: 0.61) [43]. In contrast, contemporary headband solutions such as the CUE+ Sport Sensor, exhibit a substantial decline in reliability (combined CCC of 0.13), mainly due to soft tissue artifacts and inadequate skull coupling [43].

Consequently, a scientifically valid framework for non-helmeted sports must fundamentally address the mechanical coupling challenge. To ensure a level of fidelity comparable to intraoral devices, the proposed architecture must resolve three distinct technical requirements: (i) Mechanical stability: the design must implement a rigid or semi-rigid anchoring system to minimize the "soft tissue motion artifact", identified as the primary cause of low CCC values in the existing headbands. (ii) Temporal Resolution: to correctly reconstruct the impact curve, which in soccer headers can have a duration of only a few milliseconds, the system must support a high sampling frequency (≥1000 Hz). A lower rate would fail to capture the real peak acceleration, regardless of the headband's stability. (iii) Dynamic Range: based on the kinematic benchmarks identified in Table 1, where non-ball accidental impacts in soccer can exceed 80 g and collision peaks in other contact sports reach over 130 g, the system must incorporate sensors with a dynamic range of at least ±200 g. This provides a sufficient safety margin to capture high-intensity events without signal saturation which could lead to an underestimation of impact severity.

- Standardization and Metric Interoperability

The lack of a unified industrial standard remains a significant challenge in head impact monitoring. Currently, each manufacturer uses its own metrics, thresholds, and output formats. There is no unified industrial standard for impact sensors, making it difficult to compare results across studies or to implement technologies broadly. Some devices report only peak g-force; others use HIC (Head Injury Criterion) or proprietary "concussion risk" algorithms, so there is a need for convergence toward scientifically accepted metrics and greater interoperability (similar to how heart rate data from various heart rate monitors can be universally read).

Consequently, there is a clear necessity for convergence toward scientifically accepted, non-proprietary metrics (e.g., HIC, pLA, pRA) to ensure interoperability. In the proposed framework, the system must prioritize raw data accessibility. This approach ensures that the data can be universally interpreted and integrated into existing sideline medical protocols.

- Athlete Comfort, Compliance, and Gender-specific Biomechanics

To be adopted widely, a device must be comfortable, non-intrusive, and performance-neutral [41]. The framework's design specifically addresses the biomechanical and anatomical vulnerabilities of female athletes, such as lower neck strength and head/neck mass. The design adheres to three core ergonomic requirements: (i) Mass Minimization: the system's total mass must be restricted (<50 g) to prevent the addition of significant inertial loads. (ii) Mechanical Stability: the fixation system must adapt to diverse hairstyles and anthropometric fit to reduce the risk of motion artifacts. (iii) Usability: the design must not hinder athletic performance, allowing for unimpeded breathing, communication, and heading.

- Operational and Connectivity

To ensure effective deployment during training and competitive matches, the framework must satisfy specific operational benchmarks: (i) System autonomy: the device requires a minimum battery life of ≥8 h to cover the full duration of a match-day, including warm-up and potential overtime, without requiring recharging. (ii) Data integrity and Buffering: given the risk of signal occlusion or environmental interface in high-mobility sports like soccer, the system must incorporate on-board data buffering. This prevents data loss during wireless transmission gaps, ensuring accurate impact reconstruction for post-game analysis. (iii) Real-time latency: to support immediate sideline medical protocols (e.g., Head Injury Assessment), a target latency of <100 ms is established.

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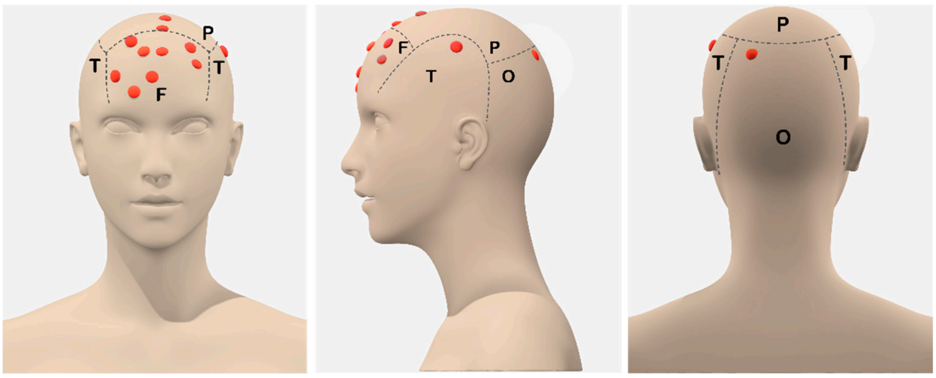
- Cost and Accessibility

Current technologies are expensive and have been primarily accessible to elite sports or research projects. While low-cost consumer option exists, they frequently sacrifice accuracy (e.g., by omitting gyroscopes). The framework aims to provide a cost-effective architecture that maintains kinematic precision. By utilizing a design based on commercially available off-the-shelf components, the system facilitates accessibility for amateur and youth women's soccer clubs.

3. Results

3.1. Ethnographic Video Analysis for Sensor Placement

The observational analysis provided empirical evidence regarding the distribution of head impacts, serving as the fundamental constraint for the hardware design. Twelve (n = 12) distinct impact events were identified and mapped onto the 3D head model (Figure 1). The quantitative distribution of these impacts is summarized in Table 4.



(**a**) (**b**) (**c**)

Figure 1. Cumulative map of head impact locations observed during the ethnographic video analysis. The cranium is segmented into four anatomical zones delimited by dashed lines: (F) Frontal, (P) Parietal, (T) Temporal, and (O) Occipital. The red markers indicate the distinct impact events (n = 12) identified on the 3D head model across (**a**) frontal, (**b**) lateral, and (**c**) posterior views.

Table 4. Frequency and spatial distribution of head impact events observed during the ethnographic video analysis. Data corresponds to the distinct impact events (n = 12) mapped on the 3D model in Figure 1, categorized by anatomical zone and observed mechanism.

Impact Region	Number of Impacts (n)	Frequency (%)	Typical Impact Mechanism
Frontal Zone	8	66.67%	Voluntary Header (Forehead)
Parietal Zone (Top)	2	16.67%	Glancing Header/Aerial Duel
Temporal Zone (Side)	1	8.33%	Player-to-Player Collision
Occipital Zone (Back)	1	8.33%	Backward Fall/Blindside Impact
Total	12	1	

The analysis revealed a distinct spatial asymmetry in impact distribution. The Frontal Zone emerged as the most impacted site, counting 58.3% of the recorded events, mainly caused by intentional ball-to-head contact. The Parietal Zone counts 16.67% the of impacts, typically due to aerial impacts or trajectory misjudgments. The Occipital Zone registered the lowest frequency of impacts (8.33%), with one single event recorded. Notably, no impacts were registered on the lower occipital fossa throughout the analyzed footage.

These results validate the decision to use the lower posterior region as the optimal 'safety zone' for housing the system's rigid components. This placement minimizes the risk of the hardware acting as a mechanism of injury during play, while the high-frequency impact zones (Frontal and Parietal) were designated for the placement of flexible PVDF sensing strips to maximize detection sensitivity.

3.2. Proposed Monitoring Framework: Technical Architecture

To overcome the stability and accuracy gaps identified in Section 2.4, the proposed framework is structured as a modular, textile-based architecture. This design prioritizes rigid skull-coupling and high-resolution data captured through a multi-modal sensing strategy.

3.2.1. Kinematic and Sensing Specifications

The framework operationalized the design requirements by integrating the nRF52840 SoC (the core of the Arduino Nano 33 BLE Sense Rev2) into a custom printed circuit board (PCB). This configuration provides 6-axis IMU capabilities for standard kinematics and manages Bluetooth Low Energy (BLE) 5.0 wireless connectivity. To meet the clinical benchmarks for impact monitoring, the architecture incorporates a dedicated high-G triaxial accelerometer (ADXL372), interfaced via Inter Integrated Circuit (I2C), achieving a dynamic range of ±200 g and a sampling frequency of 1000 Hz.

3.2.2. Sensor Topology and Operational Logic

To overcome the limitations of single-node inertial systems, the framework utilizes a quadrant-array of four PVDF (Polyvinylidene Fluoride) piezoelectric strips. Specifically, these sensors are custom-cut from commercial PVDF film sheets to dimensions of 40 mm × 10 mm. They feature a thickness of approximately 25 μm to ensure seamless integration and possess a broad dynamic range suitable for detecting impacts from minimal contact up to high-energy collisions.

These sensors are embedded within the textile to detect localized surface pressure (1 frontal, 2 lateral, 1 occipital). The scientific core of the framework is the Temporal Correlation Logic (illustrated in Figure 2), which acts as a filter for motion artifacts. This logic ensures the system's parsimony and coherence by following a hierarchical validation flow: (1) Trigger Stage: The high-G IMU remains in a low-power wake-up mode. An impact is registered only if linear acceleration exceeds a predefined threshold (>10 g). (2) Validation Stage: Upon triggering, the system analyzes the contemporaneous signal from the PVDF array within a 10 ms synchronization window. A "true-impact" is confirmed only if a high-frequency voltage transient is detected, indicating mechanical deformation of the headband. (3) Spatial Mapping: the quadrant with the highest voltage magnitude identifies the impact site (Frontal, Lateral, or Occipital), allowing for the filtering of non-impact inertial noise (e.g., rapid head rotations or headband adjustments). While a theoretical 10 ms synchronization window is currently implemented based on impact mechanics, the specific signal activation threshold (dV/dt) will be experimentally defined. This calibration will be performed during the laboratory phase by analyzing the signal response to controlled quasi-static loading (e.g., low-velocity compression) versus dynamic impacts to effectively filter out artifacts.

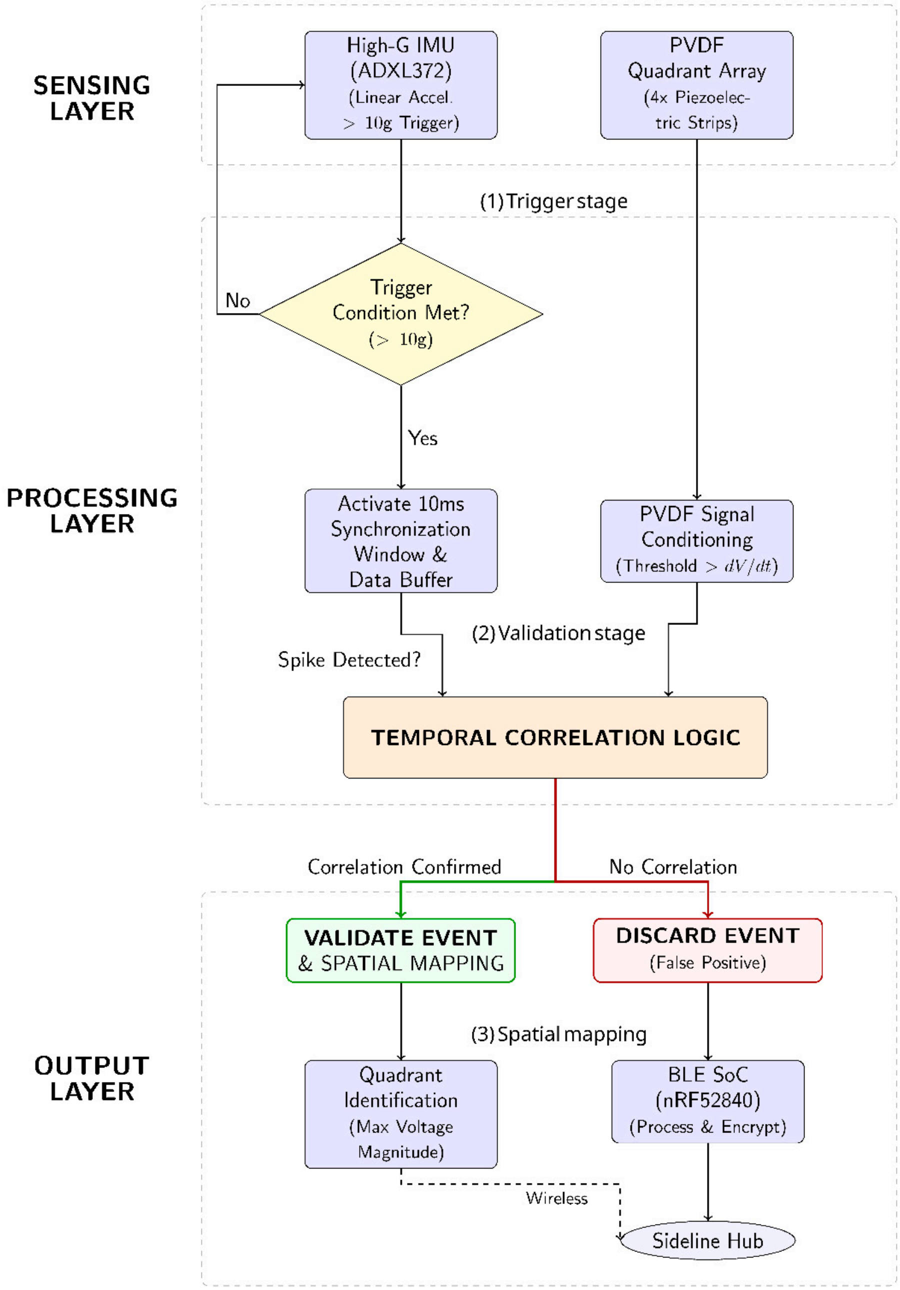


Figure 2. Functional block diagram of the proposed monitoring framework illustrating the Temporal Correlation Logic. The architecture implements a multi-modal validation strategy where kinematic triggers from the high-G IMU are cross-referenced with localized piezoelectric pressure transients from the PVDF array. This hierarchical flow is specifically designed to distinguish true head impacts from non-impact inertial noise and soft-tissue motion artifact.

3.2.3. Ergonomic and Mechanical Coupling

The physical architecture is optimized for the female athletic profile through specific design choices:

- Occipital Sensor Placement: The electronics (SoC, battery, and high-G sensor) are protected by a semi-rigid Thermoplastic Polyurethane (TPU) enclosure (estimated dimensions: 45 mm × 25 mm × 10 mm) positioned in the occipital pocket (Figure 3), accommodating diverse hairstyles and protecting the core from direct headers.
- Stabilization: To mitigate soft tissue motion artifacts and prevent device migration (slippage) caused by perspiration, the design implements a differential friction strategy.

High-grip silicone patterns are applied to the frontal and temporal areas to anchor the device against the skin. In contrast, the posterior section relies on a textured, non-adhesive fabric designed to resist vertical slipping; this approach avoids the hair pulling and discomfort often caused by full silicone strips.

- Mass Optimization: the integrated architecture targets a total mass below 50 g, satisfying the requirement for minimal inertial loading on the neck.
- Wiring and Signal Integrity: The framework utilizes ultra-thin flexible ribbon cables embedded within a protective textile channel to connect the PVDF sensors to the occipital hub. To prevent noise or cross-talk between the multiple channels, the wiring uses shielded micro-cables and a centralized grounding plane. This ensures stable impedance and preserves the high-fidelity signal required for accurate impact reconstruction.
- Modular Integration and Maintenance Strategy: long-term adoption requires the maintenance of hygiene standards without compromising electronic integrity. The framework implements a modular extraction strategy, decoupling the sensing core from the textile chassis. This ensures that the passive textile component can undergo standard sanitization cycles, preserving the electrochemical stability of the sensor against sweat accumulation.

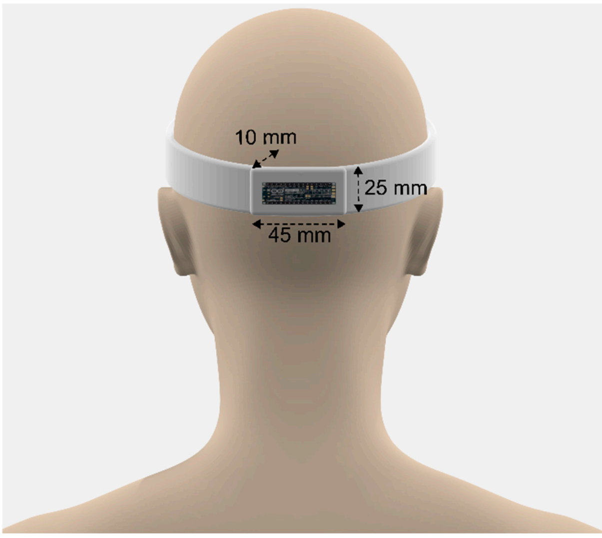


Figure 3. Posterior view of the proposed wearable device illustrating the occipital sensor placement. The semi-rigid TPU enclosure, housing the core electronics (SoC and IMU), is positioned within the identified "safety zone" to minimize impact risk. Dimensional annotations (in mm) define the component's footprint (45 mm× 25 mm× 10 mm).

3.2.4. Operational Workflow and Connectivity

To ensure reliability in complex environments, such as stadiums with high electromagnetic interference, the framework incorporates specific communication and security protocols:

- Resilience to Interference: In environments with thousands of active devices (e.g., fans' smartphones), BLE 5.0 utilizes Frequency Hopping Spread Spectrum (FHSS). The framework is designed to prioritize the advertising packets of the headbands, ensuring that the critical impact alert signal can bypass channel congestion to reach the sideline receiver.
- Sideline Infrastructure and App Integration: The system connects directly to a dedicated Sideline Hub (a tablet or laptop) via a centralized gateway. This gateway can manage multiple headbands simultaneously. The data is visualized through a custom

application that provides immediate alerts based on the thresholds defined for the sport-specific impacts.

- Data security and Privacy: to comply with medical data standards (e.g., General Data Protection Regulation (GDPR)), the transmission is encrypted at the hardware level. Each device is paired with a unique ID, ensuring that sensitive biomechanical data is only accessible to authorized medical staff and not interceptable by third parties.

3.3. Economic Feasibility Analysis

To ensure the system meets the requirement for economic accessibility in grassroots sports, a preliminary Bill of Materials (BOM) analysis was conducted based on high-volume commercial component pricing. The architecture prioritizes COTS (Commercial off-the-shelf) components to minimize costs without compromising signal fidelity. Specifically, the integration of the nRF52840 SoC directly onto a custom PCB, combined with the dedicated high-G ADXL372 accelerometer, LiPo battery and the custom-cut PVDF arrays (sourced from standard commercial piezoelectric films), results in an estimated hardware production cost of approximately \$50–\$60 USD per unit. This projection represents a potential ~90% cost reduction compared to current professional-grade instrumented mouthguards.

4. Discussion

4.1. Sensor Topology and Accuracy Target

The hardware layout has been defined based on ethnographic video analysis, which indicated that the occipital region is the area least subject to direct impacts during match play. The positioning of rigid electronic components in this zone has been chosen to reduce the risk of the device itself becoming a mechanism of injury during intentional headers and to protect the hardware from mechanical shock. However, it must be acknowledged that this placement represents a strategic choice based on qualitative observations of impact frequency rather than prior kinematic optimization. The current literature indicates a significant accuracy gap between instrumented mouthguards (CCC~0.97) and existing headband mounted sensors (CCC~0.13–0.45), primarily driven by soft tissue motion artifacts. While the occipital area appears less exposed to trauma, empirical testing is required to verify whether this position allows for an accurate reconstruction of impacts occurring on the frontal or lateral zones of the head. To bridge this accuracy gap, a validation logic has been integrated into the framework. By coupling the IMU with PVDF pressure sensors, the system has been designed to distinguish between true mechanical impacts and non-impact inertial movements. This objective validation aims to ensure that the data captured by the headband reflects actual impact events, addressing the common issue of false positives in wearable head-impact monitors.

4.2. Operational Feasibility, Versatility and Gender-Specific Design

To address the economic barriers limiting adoption in amateur leagues, the framework has relied on COTS components. A preliminary bill of materials analysis has suggested a hardware cost of approximately \$50–\$60 USD, making team-wide deployment more sustainable than current commercial solutions. Furthermore, an open-architecture approach has been adopted, utilizing standard BLE protocols rather than proprietary algorithms, to ensure interoperability with generic third-party analytics platforms.

In addition to safety, the system, if desired, could also track performance. By setting the accelerometer thresholds to lower values (e.g., 3 g–5 g), the device can measure external workload metrics like sprints, jumps, and cumulative player load. This dual functionality is especially valuable for amateur clubs, offering a single, affordable tool that covers both injury prevention and athletic monitoring. From a biomechanical perspective, the design addresses the distinct anatomical features of female athletes, such as lower neck muscle strength and head-neck segment mass. These factors increase susceptibility to rotational acceleration and motion artifacts; therefore, the target mass of less than 50 g and the use of a high-grip biomimetic interface have been established as functional requirements to ensure stable skull coupling.

4.3. Limitations and Future Developments

The work presented constitutes a theoretical framework and design proposal; no physical prototype has yet been validated under field conditions.

Finally, regarding the videographic analysis, it is important to acknowledge that the sample size (n = 12 impacts) is limited and preliminary. This analysis was not intended to provide a generalized epidemiological profile of head impacts in women's soccer, but rather to serve as a design constraint identification tool. It is acknowledged that a larger dataset might reveal greater variability in impact locations. Consequently, the current 'occipital safety zone' designation is a theoretical requirement that will be subject to verification during the field-testing phase of the prototype.

While the sensor placement has been informed by ethnographic video analysis, the effectiveness of the sensor logic remains to be proven. Moreover, environmental and anatomical variables present distinct challenges. Specifically, the friction coefficient is strongly influenced by the presence of sweat at the sensor-skin, which can lead to device mitigation. To address this limit, the framework suggested employs a differential friction strategy with high-grip silicone on the band at the forehead and temples, and a textured, non-adhesive fabric on the back section to resist vertical movement. Future testing must verify that this solution works effectively across different hairstyles without affecting signal quality.

The next phase focuses on physical prototyping and laboratory calibration over a projected 6-month timeline, using a standard National Operating Committee on Standards for Athletic Equipment (NOCSAE) headform and a linear impactor. This testing aims to establish precise voltage thresholds for the PVDF sensors, following ASTM F2439 protocols [67]. For this prototype stage, successful validation is defined by achieving a CCC > 0.90 and a Peak Relative Error (RE) < 10% when compared to reference instrumentation. Subsequently, pilot studies with female athletes will be required to assess comfort and performance in the field, verifying mechanical integrity and zero decoupling under real-world play conditions.

Future field validation protocols will be designed in strict compliance with the General Data Protection Regulation (GDPR) and relevant local data protection laws. A robust data management plan will be implemented, prioritizing participant privacy through pseudo-anonymization.

5. Conclusions

This study has presented a theoretical framework for a head-impact monitoring device specifically tailored to the biomechanical and ergonomic needs of female soccer players. Based on the identified literature and market gaps, the design prioritized a system mass below 50 g to minimize rotational inertia and a rigid skull-coupling strategy to address the low accuracy typical of existing headbands. The integration of ethnographic video analysis provided empirical evidence identifying the lower occipital fossa as a "safe zone", enabling a hardware placement that minimizes injury risk during heading. To overcome the limitations of current wearable technology, the proposed architecture introduced a novel multi-modal sensing strategy (IMU + PVDF) designed to filter non-impact inertial artifacts and reduce false positives.

It is acknowledged that this study represents a concept design and requirements analysis; the system has not yet undergone physical validation. Consequently, the transition from this conceptual framework to application requires a structured validation phase. The next steps focus on building the prototype and calibrating it against reference accelerometers using standard impactor tests (ASTM F2439). Field trials will then follow to confirm signal stability during actual play. By merging safety-driven sensor placement with an open, affordable design, this framework offers a scalable foundation for managing injury risk in amateur and youth leagues.

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Abbreviations

The following abbreviations are used in this manuscript:

IMU	Inertial Measurement Unit
PPG	Photoplethysmography
NCAA	National Collegiate Athletic Association
SoC	System on a Chip
PCB	Printed Circuit Board
TPU	Thermoplastic Polyurethane
FHSS	Frequency Hopping Spread Spectrum
GDPR	General Data Protection Regulation
NOCSAE	National Operating Committee on Standards for Athletic Equipment
BOM	Bill of Materials

Appendix A Comparative Analysis of Established Contact Sports

This appendix provides a detailed review of the impact kinematics and concussion management protocols in American Football, Rugby, Taekwondo, Boxing and Ice Hockey. These data were analyzed as a preliminary benchmark to establish technical performance standards required for the development of the soccer-specific monitoring system described in the main text.

- American Football;

American football is characterized by a high frequency of sub-concussive impacts accumulated over the course of a season. Instrumented helmet and mouthguard studies indicate that the majority of routine impacts fall within the range of a few g to several tens of g [29,68–70]. For example, an on-field study, conducted during a Canadian football game, using an instrumented mouthguard, recorded 53 valid impacts out of 302 triggered events. The measured peak linear accelerations (pLA) ranged from 11.2 to 82.7 g (mean: 31.7 ± 17.7 g), while peak rotational accelerations (pRA) ranged from 495 to 5205 rad/s^2 (mean: 2072 ± 112 rad/s^2) [71]. The directionality of impacts plays a key role in injury risk: frontal blows to the facemask produce higher linear accelerations, whereas lateral or posterior impacts transmit larger rotational accelerations. The National Football League (NFL) has implemented concussion management protocols for American football at the professional level. This protocol is continuously updated in line with scientific evidence and includes the 2016 Berlin Consensus Statement on Concussion in Sport [72]. The current NFL protocol includes preseason baseline testing, continuous gameday surveillance by medical teams, standardized in-game concussion assessment tools, and structured return-to-play guidelines. These measures, developed in collaboration with medical experts, exemplify a multidisciplinary approach to concussion prevention and management [73].

- Rugby;

Rugby has one of the strictest in-game concussion management systems, known as the Head Injury Assessment (HIA) protocol. This is a complex process designed to identify players with a confirmed or suspected concussion and to guide their consequent management. The protocol includes three stages: (i) an initial on-pitch and/or pitch-side evaluation immediately after the injury, (ii) a follow-up assessment within three hours, and (iii) a further clinical assessment at 36–48 h [74]. If a player exhibits signs of possible concussion (e.g., loss of balance, disorientation, vacant stare), they are immediately removed from play for an evaluation by medical staff.

In rugby, the only standard protective equipment is the mouthguard. Recently, instrumented mouthguards have been used in elite competitions to provide real-time data on head impact kinematics, including peak linear and rotational accelerations. According to a recent systematic review by De Sousa-De Sousa et al., (2025) [75], the mean pLA in rugby union impacts was 17.35 g (95% CI: 14.68–20.02 g), while in rugby league it was 25.19 g (95% CI: 7.64–42.73 g). The corresponding mean pRA for rugby union was 1259.51 rad/s^2 (95% CI: 1112.12–1406.91 rad/s^2). These values are considerably lower than those observed in helmeted collision sports, but their high frequency accentuates the increasing risk of repetitive sub-concussive impacts in rugby.

- Taekwondo and Boxing;

Research on head injuries in boxing and taekwondo reveals significant biomechanical differences. Taekwondo kicks generate higher impact forces than boxing punches, with roundhouse kicks producing greater pLA (130.11 $\pm$ 51.67 g vs. 71.23 $\pm$ 32.19 g) and pRA (10,927 $\pm$ 8017 rad/s^2 vs. 9306 $\pm$ 4485 rad/s^2) compared with boxing techniques [76,77]. Current protective headgear in both sports demonstrates inadequate impact attenuation, failing to meet the American Society for Testing and Materials (ASTM) safety standards by not reducing linear acceleration below the 150 g threshold [78]. Concussion incidence in taekwondo ranges from 0.0 to 50.2 per 1000 athlete-exposures (median: 4.9), exceeding rates in American football and ice hockey but remaining lower than boxing [79]. According to a systematic review by Loosemore et al., (2015) the most common injury locations in boxing within the head region are the face and scalp, followed by the nose, chin, and jaw [80].

The Association of Ringside Physicians (ARP) and USA Boxing Concussion have established the immediate removal of an athlete from competition if a concussion is suspected [81]. The minimum suspension spans from 30 days, for technical knockouts or knockouts without loss of consciousness, up to 180 days for knockouts with long loss of consciousness or repeated incidents [82]. All fighters, including the winners, must undergo a post-bout evaluation for concussion signs and symptoms [81]. Return-to-play rules follow a strict phased protocol, requiring an initial period of rest (at least one week), gradual activity progression, and specialist medical visit before returning to contact activities [81].

- Ice Hockey;

Ice hockey has one of the highest concussion rates in sport, with reported incidence ranging from 0.54 to 1.18 per 1000 athlete-exposures [83]. The sport's aggressive, high-speed nature creates substantial injury risk, particularly head trauma [84]. Using instrumented helmet, Wilcox et al., (2014) quantified pLA at 41.6 g (95% CI: 36.6–49.5) for male and 40.8 g (95% CI: 36.5–49.9) for female collegiate players, and pRA at 4424 rad/s^2 (95% CI: 4076–5182) for males and 3409 rad/s^2 (95% CI: 3152–3839) for females [85]. An evaluation of impact as a function of location on the helmet, showed that impacts to the back of the head produced greater 95th percentile pLA than impacts to the front, top, and side for both male and female players [85]. Epidemiological studies report that the most frequent head injury locations in ice hockey are the occipital and parietal regions (back and sides of the head), typically resulting from collisions with the boards or falls to the ice [86].

Current concussion management in ice hockey relies heavily on mandatory removal from play, structured sideline evaluation, and six-step return-to-play instructions. Nevertheless, the reporting of subjective symptoms remains a significant contributing factor [83,87].

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