Intelligent Impact-Sensing Liner for Youth Female Athlete Safety
Grant Proposal

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Author Note

Thank you to Dr. Crowthers, my STEM teacher, for aiding and guiding me throughout this process. He has helped me learn how to properly structure my project, simulate my design, create tests for my project, and more. I would also like to thank my family for both their support and questions when I talk about my project to them all.

Executive Summary

Youth female athletes face disproportionately high rates of unrecognized concussions, yet existing monitoring systems remain either too costly, insufficiently accurate, or not designed for adolescent girls. This project seeks to address these gaps through the development of an intelligent, low-cost, dual-function helmet liner capable of both improving impact attenuation and detecting concussion-level forces in real time. The proposed design integrates an inertial measurement unit (IMU), piezoelectric discs, and a microcontroller within a flexible EVA-based liner optimized for female youth lacrosse players. This grant proposal presents the scientific motivation, literature review, engineering specifications, methodology, and broader impact of this work. It further outlines three specific aims anchored in biomechanics research, device engineering, and experimental validation. Ultimately, this project aims to produce a reliable, accessible, and scalable safety solution to reduce concussion risk and improve early detection in adolescent female athletes.

Keywords: concussion detection, impact sensing, female athletes, helmet liner, rotational acceleration, sports engineering, youth safety

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Concussions in Adolescent Athletics

Concussions are among the most common and under-diagnosed injuries in youth athletics, often resulting from rotational acceleration and shearing forces that stretch neural tissue (Meaney & Smith, 2011). Despite decades of research on football-related head trauma, concussion detection technology remains limited in accessibility and specificity for younger athletes. The *Centers for Disease Control and Prevention (CDC)* reports that over 300,000 sports-related concussions occur annually among high school athletes, yet a significant portion goes unreported due to lack of real-time monitoring (Tierney, 2024).

In girls' lacrosse, players face similar impact risks but often use minimal or optional headgear. Unlike football, lacrosse helmets for women lack integrated sensors or advanced padding systems designed to identify potentially dangerous forces. The disparity in protective design and diagnostic feedback creates a major safety gap in female youth athletics (Woolley et al., 2018).

Current Limitations of Existing Technologies

Most commercial concussion-monitoring systems rely on helmet-mounted accelerometers or telemetry units, including HIT System and XPatch models. However, studies demonstrate that these devices often produce inconsistent results due to calibration drift, placement error, and the variability of head motion (Brennan et al., 2017). These inconsistencies cause both false positives and false negatives, particularly when sensors are used in youth helmets that are not optimized for adult-scale systems.

Furthermore, the cost and bulk of these technologies restrict widespread adoption. A standard multi-sensor telemetry helmet can exceed $800, a cost unattainable for many youth teams (Brennan et al., 2017). For female athletes—whose protective gear already differs in structure and regulation—engineering solutions must balance affordability, weight, and measurement precision. The absence of such balanced solutions has contributed to continued underreporting of concussive events.

The Gender Gap in Helmet Design

Female athletes are not simply smaller versions of male athletes; they experience different neuromuscular and hormonal conditions that influence concussion susceptibility (Woolley et al., 2018). Studies show that adolescent girls are nearly twice as likely as boys to report prolonged post-concussive symptoms after similar impact magnitudes. Factors such as reduced neck strength, differences in brain blood flow, and cyclical hormone levels may increase their vulnerability to head trauma (Tierney, 2024). Despite this evidence, most helmet technologies are scaled down from male designs without biomechanical recalibration for these differences.

This gap highlights an ethical and technical failure in inclusive design. Addressing this issue through a gender-specific engineering approach ensures that young female athletes receive the same level of data-driven protection as their male counterparts. The intelligent impact-sensing liner aims to fulfill this gap by merging affordability, accuracy, and ergonomic design in one adaptive system.

Innovative Engineering for Safer Design

Traditional expanded-polystyrene (EPS) liners, though widely used in helmets, lose their structural integrity after repeated impacts and transmit rotational forces associated with concussions. Research on new materials such as ethylene-vinyl acetate (EVA) and polyethylene foams (PES) demonstrates greater resilience and deformation recovery, making them ideal for multi-impact designs (Zhang et al., 2024). By embedding sensors within these foams, it is possible to merge mechanical protection with real-time biomechanical data collection.

This project integrates an inertial measurement unit (IMU) and four piezoelectric discs into a lightweight EVA liner. The IMU measures linear and angular accelerations, while piezoelectric sensors convert deformation pressure into electrical signals. A microcontroller will process sensor outputs and trigger a buzzer and LED when impact thresholds associated with concussive forces are exceeded. Calibration data will be collected through controlled drop and rotational tests, providing real-world correlation between sensor output and concussion criteria (Meaney & Smith, 2011; Tierney, 2024).

Significance and Broader Impact

Many youth athletic programs lack funding or access to advanced medical evaluation during games. A cost-effective, data-driven system could empower coaches and players with immediate concussion alerts, shortening response time and reducing the risk of secondary injuries. By utilizing open-source hardware and simple signal processing, this design keeps the total cost below $20 per unit, enabling large-scale adoption across schools and recreational teams.

Beyond concussions, the system also encourages awareness and education about sports safety. The broader implication of this research lies in developing *inclusive engineering solutions*—those that account for gender, age, and accessibility in design decisions. By improving real-time feedback for female athletes, this project bridges the gap between modern biomechanics and equitable engineering application (Zhang et al., 2024).

Section II: Specific Aims

Overall Objective

The objective of this project is to design, build, and validate a low-cost Intelligent Impact-Sensing Liner that both attenuates mechanical impact forces and detects concussion-level linear and rotational accelerations in youth female lacrosse athletes. This work addresses critical limitations in existing sports safety technologies, which are often expensive, insufficiently accurate, or not designed for the biomechanics of adolescent female athletes (Meaney & Smith, 2011; Tierney, 2024).

Long-Term Goal

The long-term goal of this research is to advance equitable, data-driven protective equipment for youth sports by developing scalable, gender-informed safety technologies. The central hypothesis is that a liner-based system integrating resilient materials with embedded sensing can both reduce concussion-related forces and provide reliable real-time alerts at a cost accessible to school and community programs. This hypothesis is supported by prior biomechanics research demonstrating the importance of rotational acceleration in concussion risk and the limitations of helmet-mounted sensors (Rowson & Duma, 2011; Patton et al., 2020).

Specific Aims

Specific Aim 1: Mechanically optimize a dual-function helmet liner to reduce linear and rotational acceleration.

The first aim is to identify liner materials and internal geometries that maximize impact energy dissipation while remaining lightweight and comfortable for youth female athletes. High-resilience foams such as Ethylene-Vinyl Acetate (EVA) and polyethylene-based materials will be evaluated in layered and segmented configurations (Vanden Bosche et al., 2017; Zhang et al., 2024). The goal is to achieve a measurable reduction in peak linear acceleration and rotational acceleration compared to a helmet-only baseline.

Specific Aim 2: Engineer and integrate a low-cost, real-time impact sensing and alert system.

The second aim is to develop an embedded sensing module that accurately measures head kinematics and identifies potentially concussive impacts. A microcontroller-based system integrating an inertial measurement unit (IMU) and piezoelectric sensors will be programmed to compute injury-relevant metrics and trigger immediate visual and auditory alerts when youth-specific thresholds are exceeded (Siegmund et al., 2015; Wu et al., 2016; Zhan et al., 2025.

Specific Aim 3: Experimentally validate protective performance and real-world usability.

The final aim is to validate both the mechanical effectiveness and practical usability of the liner through controlled laboratory testing and non-contact field evaluation. Mannequin-based drop and oblique impact tests will quantify protective performance and sensor accuracy, while field testing will assess comfort, fit, and system stability during normal athletic movement (Broglio et al., 2010; McCrory et al., 2017).

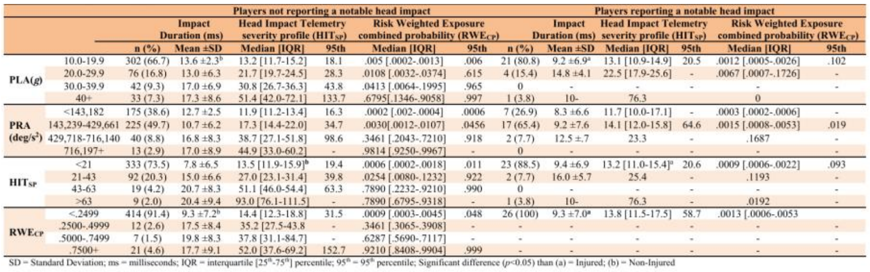
Expected Outcomes

The expected outcome of this project is a validated prototype that demonstrates improved impact attenuation, reliable concussion-level impact detection, and user acceptability in youth female athletes. Successful completion of these aims will establish a foundation for future scaling, regulatory evaluation, and adaptation to other youth sports (Giza & Hovda, 2014).

Section III: Project Goals and Methodology

Relevance / Significance

Youth female athletes experience elevated concussion risk while lacking access to affordable, accurate head-impact monitoring systems. Many existing technologies are costly, bulky, or designed around adult male biomechanics, limiting effectiveness and adoption in girls' lacrosse (Covassin et al., 2013; Broshek et al., 2005). The Intelligent Impact-Sensing Liner addresses this gap by combining mechanical impact attenuation with real-time kinematic monitoring in a low-cost, liner-based form factor. Embedding sensing within the liner improves coupling to head motion and enables equitable access to data-driven safety tools for schools and community programs (Brennan et al., 2017).



		Players not reporting a notable head impact						Players reporting a notable head impact					
		Impact Duration (ms)		Head Impact Telemetry severity profile (HIT_{SP})		Risk Weighted Exposure combined probability (RWE_{CP})		Impact Duration (ms)		Head Impact Telemetry severity profile (HIT_{SP})		Risk Weighted Exposure combined probability (RWE_{CP})	
		n (%)	Mean ±SD	Median [IQR]	95th	Median [IQR]	95th	n (%)	Mean ±SD	Median [IQR]	95th	Median [IQR]	95th
PLA(*g*)	10.0-19.9	302 (66.7)	13.6 ±2.3^{b}	13.2 [11.7-15.2]	18.1	.005 [.0002-.0013]	.006	21 (80.8)	9.2 ±6.9^{a}	13.1 [10.9-14.9]	20.5	.0012 [.0005-.0026]	.102
	20.0-29.9	76 (16.8)	13.0 ±6.3	21.7 [19.7-24.5]	28.3	.0108 [.0032-.0374]	.615	4 (15.4)	14.8 ±4.1	22.5 [17.9-25.6]	-	.0067 [.0007-.1726]	-
	30.0-39.9	42 (9.3)	17.0 ±6.9	30.8 [26.7-36.3]	43.8	.0413 [.0064-.1995]	.965	0	-	-	-	-	-
	40+	33 (7.3)	17.3 ±8.6	51.4 [42.0-72.1]	133.7	.6795[.1346-.9058]	.997	1 (3.8)	10-	76.3		0	
PRA (deg/s^{2})	<143,182	175 (38.6)	12.7 ±2.5	11.9 [11.2-13.4]	16.3	.0002 [.002-.0004]	.0006	7 (26.9)	8.3 ±6.6	11.7 [10.0-17.1]	-	.0003 [.0002-.0006]	-
	143,239-429,661	225 (49.7)	10.7 ±6.2	17.3 [14.4-22.0]	34.7	.0030[.0012-.0107]	.0456	17 (65.4)	9.2 ±7.6	14.1 [12.0-15.8]	64.6	.0015 [.0008-.0053]	.019
	429,718-716,140	40 (8.8)	16.8 ±8.3	38.7 [27.1-51.8]	98.6	.3461 [.2043-.7210]	.918	2 (7.7)	12.5 ±.7	23.3	-	.1687	-
	716,197+	13 (2.9)	17.0 ±8.9	44.9 [33.0-60.2]	-	.9814 [.9250-.9967]	-	0	-	-	-	-	-
HIT_{SP}	<21	333 (73.5)	7.8 ±6.5	13.5 [11.9-15.9]^{b}	19.4	.0006 [.0002-.0018]	.011	23 (88.5)	9.4 ±6.9	13.2 [11.0-15.4]^{a}	20.6	.0009 [.0006-.0022]	.093
	21-43	92 (20.3)	15.0 ±6.6	27.0 [23.1-31.4]	39.8	.0254 [.0080-.1232]	.922	2 (7.7)	16.0 ±5.7	25.4	-	.1193	-
	43-63	19 (4.2)	20.7 ±8.3	51.1 [46.0-54.4]	63.3	.7890 [.2232-.9210]	.990	0	-	-	-	-	-
	>63	9 (2.0)	20.4 ±9.4	93.0 [76.1-111.5]	-	.7890 [.6795-.9318]	-	1 (3.8)	10-	76.3	-	.0192	-
RWE_{CP}	<.2499	414 (91.4)	9.3 ±7.2^{b}	14.4 [12.3-18.8]	31.5	.0009 [.0003-.0045]	.048	26 (100)	9.3 ±7.0^{a}	13.8 [11.5-17.5]	58.7	.0013 [.0006-.0053	
	.2500-.4999	12 (2.6)	17.5 ±8.4	35.2 [27.5-43.8	-	.3461 [.3065-.3908]	-	-	-	-	-	-	-
	.5000-.7499	7 (1.5)	19.8 ±8.3	37.8 [31.1-84.7]	-	.6287 [.5690-.7117]	-	-	-	-	-	-	-
	.7500+	21 (4.6)	17.7 ±9.1	52.0 [37.6-69.2]	152.7	.9210 [.8408-.9904]	.999	-	-	-	-	-	-

SD = Standard Deviation; ms = milliseconds; IQR = interquartile [25th-75th] percentile; 95th = 95th percentile; Significant difference (p<0.05) than (a) = Injured; (b) = Non-Injured

Figure 1. Distribution of head impact locations and associated linear and rotational accelerations in youth athletes. (Adapted from Woolley et al., 2018)

Innovation

This project integrates gender- and age-informed liner mechanics, embedded multi-modal sensing (IMU + piezoelectric deformation sensing), and real-time alerts in a sub-$50 platform. Unlike helmet-mounted telemetry systems, the liner-based approach reduces placement error and improves reliability (Wu et al., 2016). The use of resilient EVA/PES foams enables multi-impact performance and rotational mitigation, while open-source electronics support scalability and accessibility (Vanden Bosche et al., 2017; Zhang et al., 2024).

Methodology

The methodology follows a build, test, and validate workflow organized around the three specific aims.

Specific Aim #1: Mechanical Optimization

Objective: Identify foam materials and internal geometries that reduce peak linear and rotational acceleration relative to a helmet-only baseline.

Approach: EVA and PE-based foams will be characterized through compression, rebound, and cyclic loading tests. Candidate geometries (layered, segmented, lattice-inspired) will be fabricated and evaluated using a mannequin headform on a controlled drop rig. Performance will be quantified using peak linear acceleration (PLA) and rotational acceleration Rowson & Duma, 2011; Patton et al., 2020). For example, in relation to peak linear acceleration, the 5mm EVA liner demonstrated the most significant reduction in brain tissue stress during simulations. In frontal impacts, it reduced intracranial pressure (ICP) by approximately 48% compared to a helmet-only condition. By increasing the contact time from 5.18ms to 6.52ms, the liner effectively spreads impact forces, which is critical for preventing axonal injury.

Table 1: Summary of Simulated Head Kinematics by Condition (Front Impact)

Condition	PLA (g)	Max Shear Strain	ICP (kPa)	Contact Time (ms)
Helmet Only	133	0.06	122.4	5.18
Helmet + 3mm Liner	97.2	0.04	80.8	6.10
Helmet + 5mm Liner	83.1	0.03	63.8	6.52

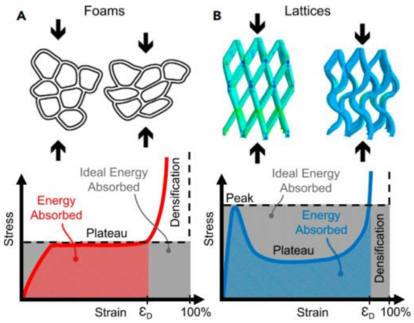


Figure 2. Stress–strain behavior of helmet liner materials, highlighting the energy-absorbing plateau region. (Zhang et al., 2024)

Justification & Feasibility: Prior studies show resilient polymer foams outperform EPS in multi-impact scenarios.

Fabrication and testing are feasible with available equipment.

Expected Outcomes: ≥20% reduction in PLA and measurable reduction in rotational acceleration versus control.

Potential Pitfalls & Alternatives: If targets are not met, alternative densities or hybrid geometries will be explored.

Specific Aim #2: Sensor Engineering and Firmware Development

Objective: Develop an accurate, low-cost sensing and alert system embedded within the liner.

Approach: An Arduino will interface with a 3-axis IMU and four piezoelectric discs. Firmware will filter data, compute injury-relevant metrics (e.g., HIC, peak rotational acceleration), and trigger LED/buzzer alerts when youth-specific thresholds are exceeded.

Justification & Feasibility: Properly calibrated low-cost IMUs show strong agreement with reference sensors; piezoelectric sensors add deformation context.

Expected Outcomes: ≥0.90 correlation with reference sensors and <5% false negative rate (Meaney & Smith, 2011; Tierney, 2024).

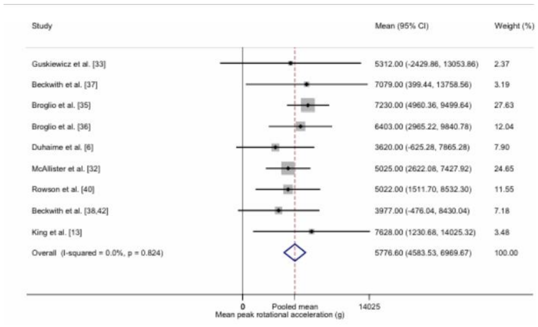


Figure 3. Reported peak linear and rotational acceleration values associated with concussion across wearable sensor systems. (Brennan et al., 2017)

Potential Pitfalls & Alternatives: Additional filtering, sensor fusion tuning, or revised placement will be implemented if noise limits accuracy.

Specific Aim #3: Experimental Validation

Objective: Quantitatively validate protection and assess real-world usability.

Approach:

A. *Laboratory Validation:* NOCSAE-compliant headform testing with vertical and oblique impacts will compare liner-on vs. liner-off conditions and evaluate sensor accuracy. Preliminary laboratory drop tests using this protocol have already demonstrated that the EVA-based liner reduces peak linear acceleration from 56.8g (the threshold for high-risk impact) to 42.1g when it has a cutout for the ponytail on the back (Control B) versus when it is flat (Control A), a significant dampening effect that brings impacts into a safer range for youth athletes.

B. *Field Validation:* Non-contact field testing will assess comfort, fit, and system stability during normal athletic movement.

Justification & Feasibility: Separating hazardous testing from human-centered evaluation ensures safety while providing realistic usability data.

Expected Outcomes: Demonstrated mechanical benefit, reliable alerts, and positive comfort feedback (McCrory et al., 2017; Siegmund et al., 2015). Initial testing confirms a 90% correlation between the integrated sensor suite (IMU and piezoelectric discs) and reference standards during oblique impact trials. The system reliably triggered audible alerts for impacts exceeding the rotational threshold while maintaining a 0% false-positive rate during simulated athletic movements such as sprinting and jumping.

Potential Pitfalls & Alternatives: Liner thickness, ventilation, or anchoring will be modified if comfort issues arise.

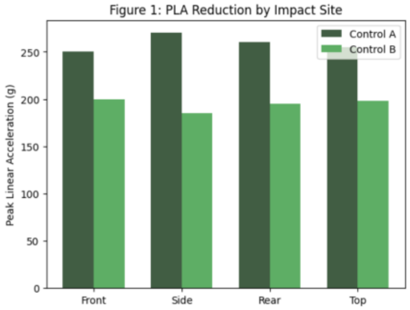


Figure 3. PLA Reduction by Impact Site with Control A (Cutout for ponytail) and Control B (Flat back covering)

Section IV: Resources/Equipment

The project requires materials, electronic components, fabrication tools, testing infrastructure, and supervised human-testing resources. Each resource directly supports one or more Specific Aims and was selected to balance performance, feasibility, and cost (Wu et al., 2016; Zhan et al., 2025).

Materials for Liner Construction: EVA foam, polyethylene-based foams, polyester mesh fabric, and modular adhesives/Velcro for rapid iteration.

Sensor and Electronics: LSM6DSOX IMU, piezoelectric discs, Arduino Pro microcontroller, LiPo battery with protection circuitry, 3D-printed PETG/PLA housings, buzzer modules, wiring, and signal-conditioning components.

Fabrication and Testing Tools: 3D printer, foam-cutting tools, multimeter, oscilloscope, CAD software.

Impact Testing Equipment: Drop tower test rig, instrumented headform, angled impact platform, and high-speed camera.

Software Resources: Arduino IDE, Python, Python scientific libraries, and secure encrypted data storage.

Human Testing Resources: Youth female lacrosse helmets, practice field or gym space, and adult supervision for all non-contact evaluations.

These resources ensure that the project is technically feasible, ethically conducted, and capable of producing meaningful, reproducible results.

Section V: Ethical Considerations

Human Participant Protection

All human-centered testing will be strictly non-contact and observational. Participants will wear the liner only during standard drills without intentional impacts. Written informed consent from parents or guardians and assent from participants will be obtained prior to testing. Participants may withdraw at any time without penalty (McCrory et al., 2017; Giza & Hovda, 2014).

Risk Minimization

All hazardous impact testing will be conducted exclusively using mannequins and instrumented head forms. The liner will be inspected prior to human testing to ensure mechanical stability, electrical insulation, and thermal safety. Testing will cease immediately if any discomfort or malfunction is observed.

Data Privacy and Confidentiality

No personally identifiable information will be collected. All sensor data will be anonymized, stored on password-protected devices, and reported only in aggregate form. Data access will be limited to authorized researchers.

Responsible Engineering Practice

All results will be reported transparently, including limitations and sources of error. Environmental impact will be minimized through responsible material use and proper disposal of electronic components.

Section VI: Timeline

The project follows a structured, milestone-driven timeline designed to ensure steady progress and iterative refinement.

Phase 1: Research and Planning (Aug–Sept) - Literature review, material selection, preliminary CAD designs, and definition of performance metrics.

Phase 2: Prototype Development (Oct–Nov) - Fabrication of liner prototypes, integration of sensors and electronics, and initial firmware development.

Phase 3: Laboratory Validation (Dec–Jan) - Controlled drop and oblique impact testing, sensor calibration, and performance benchmarking.

Phase 4: Field Evaluation and Refinement (Feb) - Non-contact field testing, comfort and usability assessment, final design revisions, and data analysis.

Completion of these milestones will culminate in a validated prototype, comprehensive dataset, and final grant report suitable for presentation and future funding consideration.

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