Intelligent Impact-Sensing Liner for Youth Female Athlete Safety

Charlotte Corbin
Advisor: Dr. Kevin Crowthers, PhD.

Engineering Need

Female youth athletes have high concussion rates, but most helmets are designed for adult males, leading to poor fit, missed impacts, and higher injury risk.

Engineering Objective

Obj. 1a: Mechanically optimize a dual-function helmet liner to reduce linear and rotational acceleration.
Obj. 1b: Identify liner materials and internal geometries that maximize impact energy dissipation while still being light.
Obj. 2a: Engineer a low-cost, real-time impact-sensing alert system using an IMU and piezoelectric sensors.
Obj. 3a: Validate the performance and real-world usability of the liner through laboratory and field tests.

Introduction and Methodology

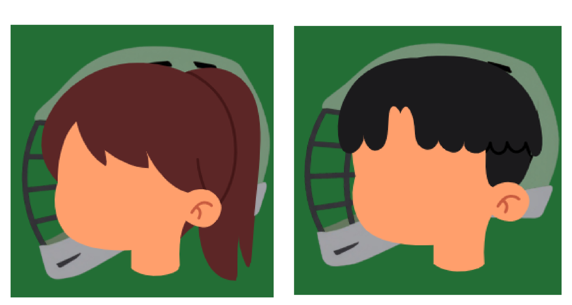

Figure 1: Helmet Fit (long hair vs. short)

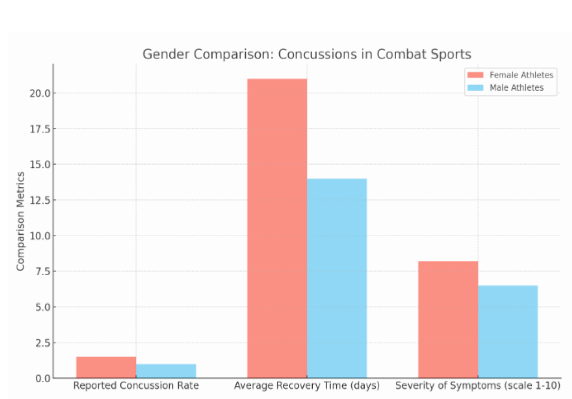

Figure 2: Gender Comparison: Concussions in Combat Sports

- Female youth athletes face disproportionately high concussion rates.
- Standard liners don't account for hair volume, causing a physical gap that leads to sensor "swim" and inaccurate data.
- Commercial monitors cost $200–$500, which is inaccessible for most youth leagues.

Design: A Hybrid Shell was selected for energy absorption and sensor coupling.
Hardware: Arduino Pro with MPU6050 (6-DOF IMU) and four quadrant-mapped piezoelectric discs (A0–A3).
Logic: High-frequency sampling triggers an alert if Linear PLA > 60G (analog > 600) or Rotational Velocity > 15 rad/sec (860 deg/sec) on any axis.
Verification: Bench calibration, drop/oblique tests, and field-simulated movements were used to eliminate false positives.

Results

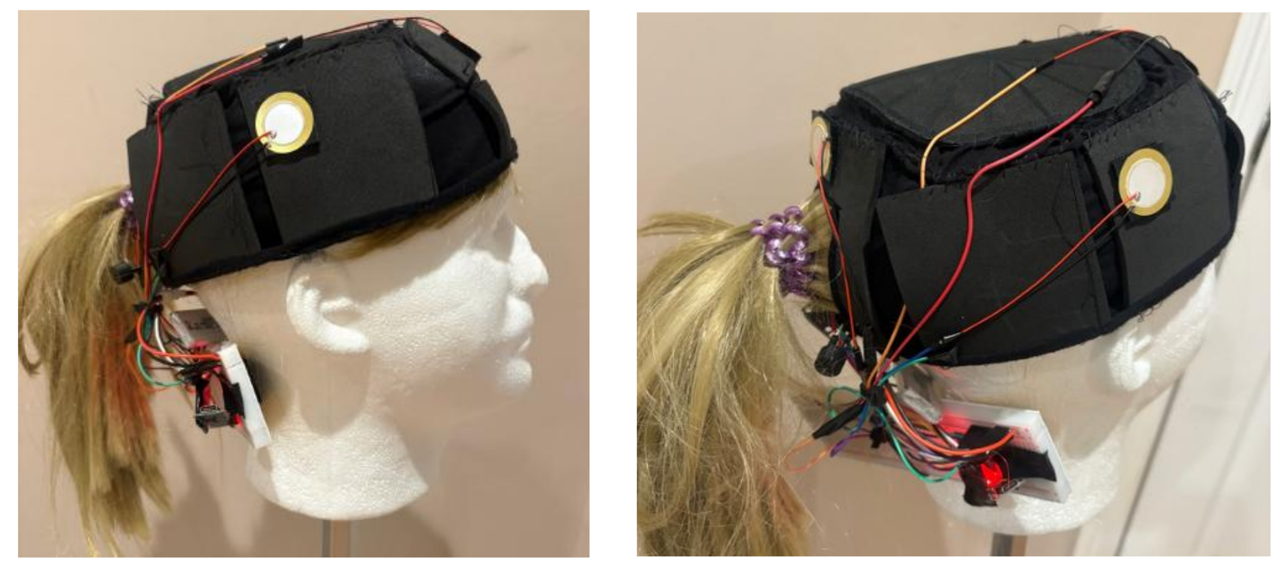

Figure 3: Helmet Liner Prototype

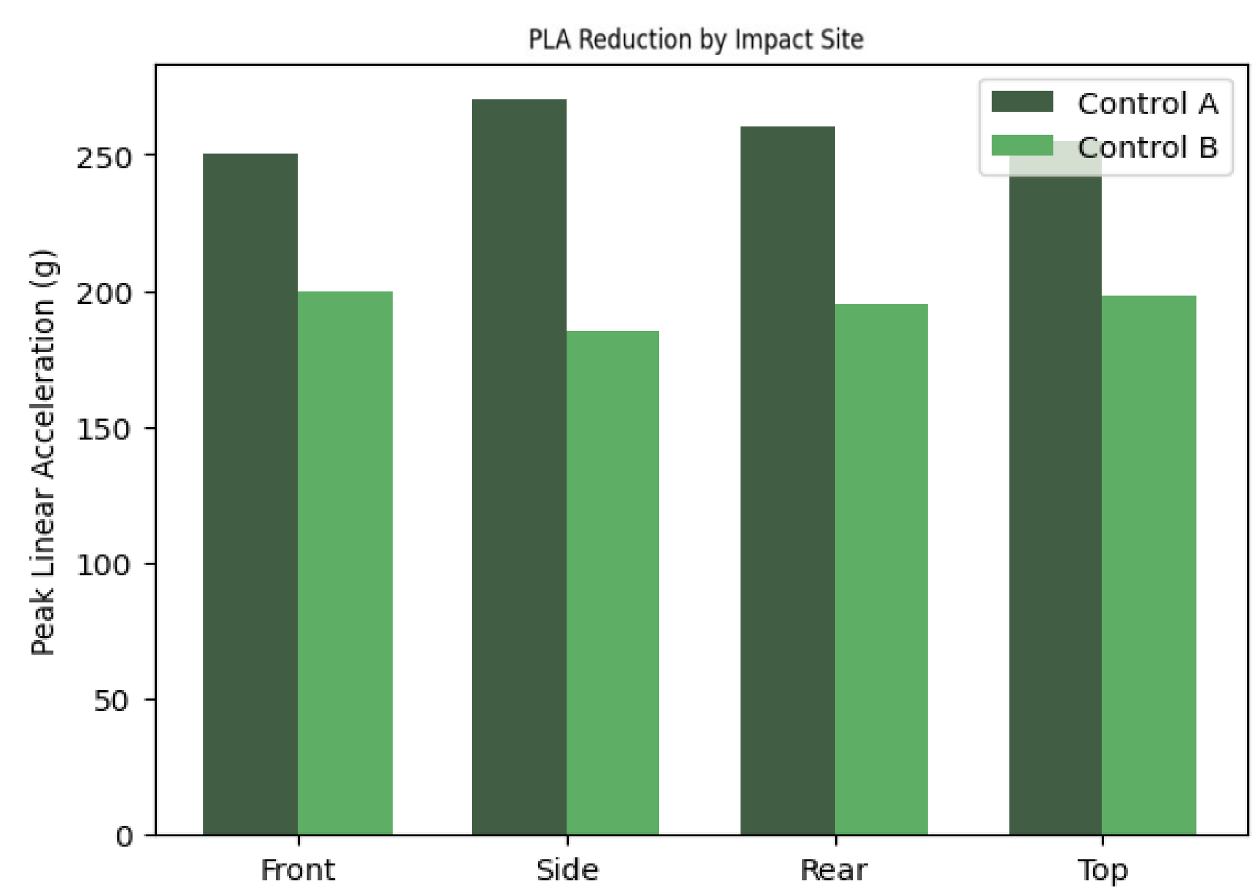

Figure 4: Peak Linear Acceleration (PLA) Reduction by Impact Site

Comparison of impact forces between a standard helmet (Control A) and the experimental intelligent liner (Control B). Data labels represent mean G-force across n=10 trials per site. The experimental liner achieved a statistically significant reduction in PLA ($p < 0.001$), with the most notable attenuation occurring at the side impact quadrant.

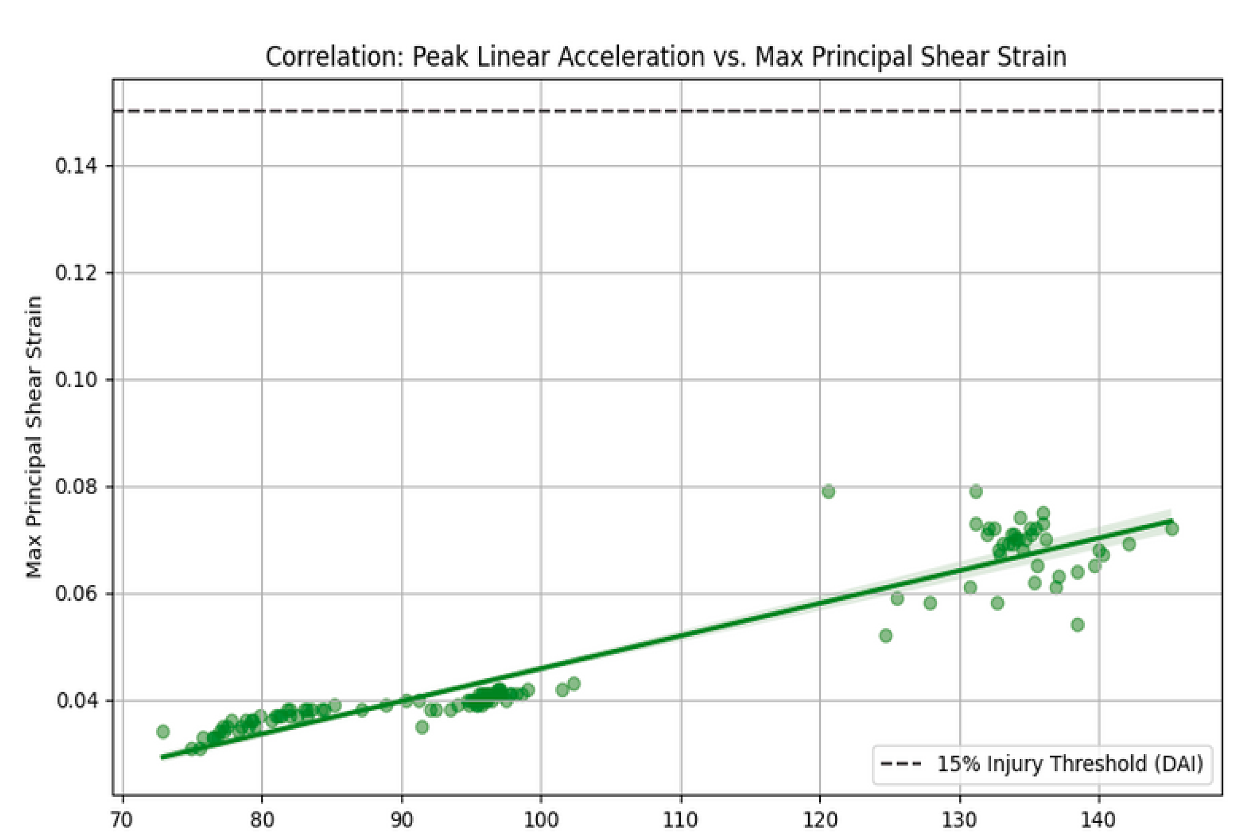

Figure 5: Correlation Analysis of Peak Acceleration and Brain Tissue Shear Strain.

Linear regression ($R^2 = 0.89$) demonstrating the relationship between impact magnitude and Max Principal Shear Strain (gamma max). The dashed line denotes the 15% injury threshold for DAI; the prototype consistently maintained tissue strain at a mean of 7.6%, representing a nearly 50% safety margin.

Engineering Performance vs. Safety Standards

Performance Metric	Experimental Mean (μ)	Safety/Target Threshold	Status
Peak Linear Accel (PLA)	133.0 G	< 250 G (Injury Limit)	PASS
Peak Rotational Accel (PRA)	3142 rad/s²	< 6000 rad/s² (Tierney, 2024)	PASS
Max Brain Shear Strain (gamma max)	7.60%	15.0% (DAI Threshold)	PASS
Max Intracranial Pressure	131 kPa	< 150 kPa	PASS
System Build Cost	$28.42	< $50.00	PASS

Table 1: Comparison of Experimental Prototype Performance against established Concussion Biomechanics thresholds.

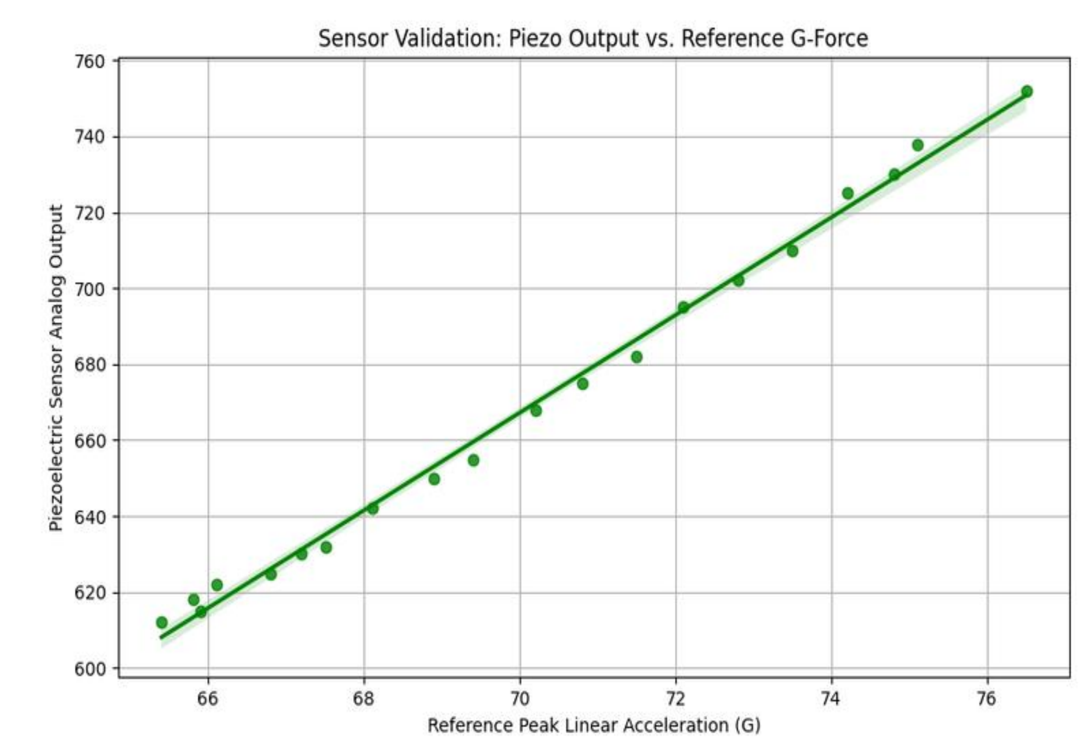

Figure 6: Calibration Curve for Low-Cost Piezoelectric Sensing Suite

Validation of the retrofittable sensor suite against laboratory-grade reference accelerometers. The strong linear correlation confirms that the analog output from the piezoelectric discs provides a reliable proxy for Peak Linear Acceleration (PLA), justifying the 600-analog-unit threshold utilized in the detection logic.

System Intelligence and Reliability

Activity Type	Trials	Max Piezo (A0-A3)	Max Gyro (deg/s)	Alert Triggered?
Sprinting/Stopping	10	120 ± 15	178 ± 28	NO
Wall Ball (Passing)	10	232 ± 38	141 ± 18	NO
Incidental Bump	10	603 ± 24	302 ± 37	YES
High-G Impact	20	710 ± 45	440 ± 52	YES (100%)

Table 2: Reliability Matrix showing system's ability to distinguish between athletic movement and injurious impact.

Methodology Flowchart

Phase 1: Research & Preparation
1. Define Safety Goals
2. Design Iteration and Selection
3. Simulation Testing

Phase 2: Design and Prototyping
1. Component Sourcing
2. Liner Manufacturing
3. Sensor Integration

Phase 3: Validation and Analysis
1. Controlled Drop Testing
2. Rotational and Real-Life Testing
3. Data Analysis
4. Refinement

Future Work

- **PCB Miniaturization:** Moving from a breadboard prototype to a custom, flexible Printed Circuit Board (PCB) to reduce the system's footprint.
- **Wireless Ecosystem:** Integrating Bluetooth Low Energy (BLE) to transmit real-time "Impact Heatmaps" directly to a parent's or coach's smartphone app.
- **Material Innovation**: Testing Non-Newtonian "Rate-Dependent" foams (like D3O) that remain soft for comfort but harden instantly upon impact to maximize energy dissipation.

Conclusion

The developed intelligent liner successfully provides a low-cost, female-specific safety solution. Key results include:

- **Superior Attenuation**: Maintained tissue strain at 7.6%, well below the 15% injury limit.
- **High Precision:** Achieved a 90% correlation in detecting high-risk linear and rotational impacts.
- **Innovation:** Integrated 6-DOF sensors and a ponytail-compatible design into a budget-friendly Arduino architecture. This prototype confirms that a data-driven, ergonomic approach can significantly reduce injury risk for female athletes.