IMU-Based Impact Characterisation of Body Armour for Use in Contact Sports

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***Abstract*— Athletes in contact sports are routinely exposed to shock impacts that may lead to acute injury or cumulative injury risk. Current wearable monitoring systems have limited capability in accurately capturing and localising short-duration, high-g impact events to the torso. This limitation is particularly significant for emerging injury concerns such as blunt breast trauma in female athletes and high-energy chest impacts, which require structured, high-quality impact exposure data. This paper presents the design and validation of a high-g, event-based inertial sensing system for detecting and characterising shock impacts on the torso surface within a laboratory environment. The proposed system employs four accelerometer nodes to localise impacts across a 2×3 grid on a surrogate torso. Interpolation methods are used to estimate the impact magnitude in adjacent regions between sensor locations. Experimental results demonstrate consistent impact detection and clear spatial dominance patterns across impact zones, with heatmap visualisations effectively identifying impact location and energy distribution. This work provides a practical foundation for torso impact characterisation and supports future development toward miniaturised, wireless in-field systems for longitudinal monitoring of athlete impact exposure.**

Keywords*— *Inertial measurement units, IMU, impact localisation, torso impact monitoring, wearable sensors

I. Introduction

Many sports expose athletes to both expected and unexpected shock impacts. A single major impact or the accumulation of repeated minor impacts, can be harmful to body structures such as muscles, bones, joints, and organs, including the brain [1]. These impacts not only affect athlete health and safety, but also athlete performance by repeated impacts wearing the athlete down throughout a match.

Current wearable technologies quantify "Player Load," defined as the collective rate of change of an athlete's acceleration, typically measured at the scapula [2]. While this technology can detect the occurrence of high acceleration impact events in rugby, it has limited capability and accuracy in characterising a range of impacts, especially low intensity [3]. This missed information is critical, as it could provide health professionals with valuable data to assess the longitudinal effects of impacts sustained during training or competition.

Chest impacts are a common occurrence in sport, and some studies suggest that it can lead to detrimental effects for the athletes involved. A study by B. J. Maron et al has shown that blunt chest impacts, usually inflicted by a projectile (such as a baseball or hockey puck), can in extreme cases, lead to sudden cardiac arrest [4]. For female athletes, breast injuries resulting from collisions and impacts are an emerging concern [5]. Few studies have investigated the effect of traumatic breast injuries and their association with contact sports, highlighting the urgent need for structured data collection and further research [5]. Collecting high-quality data through advanced wearable sensors could therefore play an important role in enhancing injury monitoring and prevention strategies across a range of sports.

Past studies have indicated that wearable sensors are not adequate to ensure valid and accurate data on detecting and localising shock impacts in the field in real time [1]. When regarding shock impacts, research has primarily focused on the head and lower body. Furthermore, there is little longitudinal monitoring of impact exposure across seasons to support coaches or clinicians in decision-making, and there is a lack of visualisation tools to translate complex data into actionable insights for stakeholders such as coaches and medical staff. Therefore, a simple low-cost (< USD$150) sensor-based system to capture and characterise the impacts is required.

II. System Design

A. Design Requirements

To characterise impact events on the torso surface, the sensing system must capture high-amplitude, short-duration acceleration transients without saturation or aliasing. The literature indicated that head acceleration events in American college football can reach peaks of up to 81g [6]. Therefore, to capture the full range of peak accelerations, a minimum acceleration range of ±100g is required. Consequently, the system requirements were defined as:

1. High-g measurement range (≥ ±100 g).
2. High sampling frequency (≥ 3200 Hz) to preserve impact signatures for later filtering and analysis.
3. Event-based logging to capture only the impact window and reduce unnecessary data volume.

To approximate torso mounting, the sensor system was attached to an impact foam base armour plate as a representative mounting surface for torso-worn sensing. The foam base has a width of 440 mm with its geometry defining the spatial bounds of the sensor system.

B. Sensor Hardware and Communication

The proposed impact sensing node was built around the Analog Devices ADXL372 triaxial accelerometer, selected for its ±200 g measurement range and 6400 Hz high sampling rate range suitable for shock events. The sensor provides 12-bit output with a scale factor of 100 mg/LSB, enabling capture of both dynamic movement and short high-g impact spikes of approximately 100 millisecond duration.

Data capture was performed using a Seeeduino v4.2 microcontroller. This was selected as the embedded host controller due to its compatibility with Arduino libraries, sufficient processing speed (up to 16 MHz), and selectable logic voltage. The board was configured for 3.3 V operation, consistent with the ADXL372 supply voltage range (1.6–3.5 V). The microcontroller performs initial sensor configuration, controls the periodic sampling, and sends the acceleration data via a serial connection to the host PC.

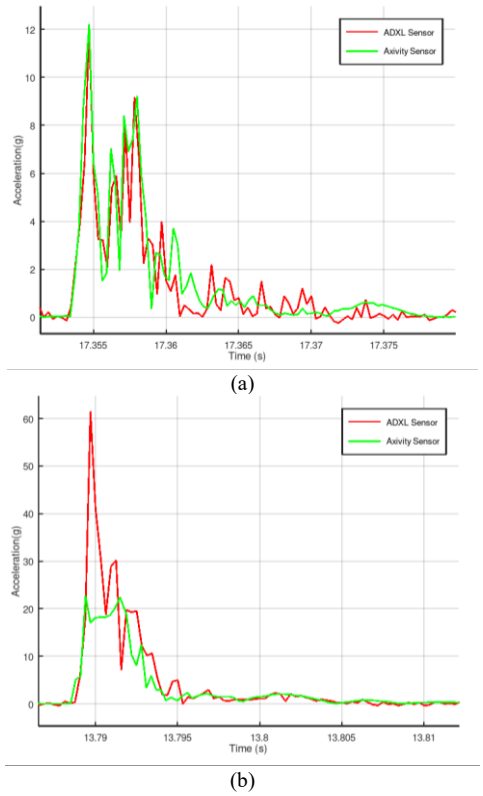


Fig. 1. Absolute acceleration comparison of the custom ADXL372 (red) Accelerometer unit and the commercial Axivity (green) accelerometer unit for impacts from drop heights of (a) 15 cm and (b) 75 cm.

Since impact events occurred over ~100 ms timescales, continuous data logging was inefficient and unnecessarily increased memory and storage requirements. Therefore, an event-based acquisition strategy was implemented using triggered capture.

A fixed-length data window is recorded when the measured acceleration exceeds a predefined threshold, while retaining a short pre-trigger history. Captured impact windows were then transmitted via serial communication to a host computer for logging and post-processing.

The ADXL372 node was configured for a 3200 Hz output data rate. Triggered acquisition was implemented using a microcontroller-based ring buffer to preserve pre-trigger samples and capture a fixed-duration event window when the threshold was exceeded. A representative configuration used a 5 g trigger threshold, a 250-sample window, and 25 pre-samples (312.5 µs sample interval).

C. Sensor Validation

The designed sensor using the ADXL372 was verified against the commercial Axivity AX3, 16 g, 3.2 kHz accelerometer which has been used extensively in sports and health research [7, 8]. This was done through systematic drop tests using a 6 cm bean bag from 75 cm and 15 cm to show comparisons where the Axivity sensor is both saturated and unsaturated. The synchronised absolute acceleration comparison of the commercial (Axivity) and custom (ADXL) accelerometer units can be seen in Fig. 1. Fig. 1(b) shows the difference in response between the two sensor units. This demonstrates that the ADXL sensor unit continued to measure higher accelerations when the Axivity sensor saturated. High impacts above 16 g are likely to occur, therefore, the ADXL is more suitable for this system.

Fig. 2 shows a statistical comparison of the unsaturated impact test between the ADXL372 and Axivity sensors, using both correlation and Bland-Altman analyses. The correlation coefficient of 0.82 indicated a strong linear relationship between the data. The Bland-Altman analysis further supported this, with 94.1% of the data points falling within the limits of agreement, meeting the expected threshold for consistency.

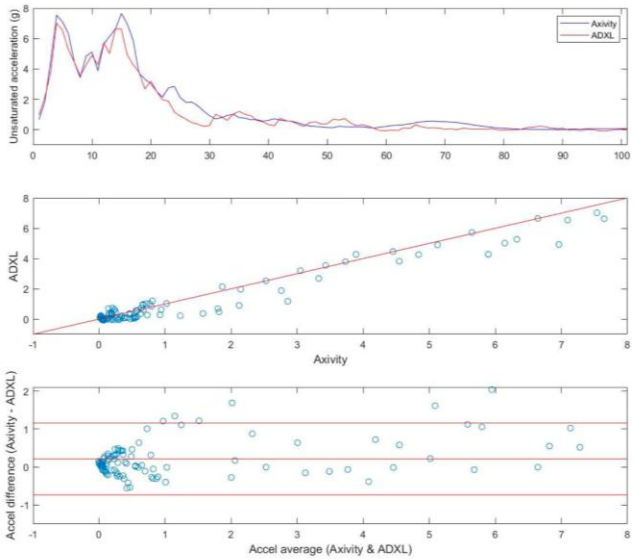


Fig. 2. (a) Raw data comparison between the Axivity and ADXL sensors, (b) correlation analysis, and (c) Bland–Altman analysis for the unsaturated 15 cm drop test.

III. Experimental Methodology

To capture data from the surface of the torso multiple factors were considered. The sensing area was confined to the

area of the chest using the armour plate as a template and the sensor resolution of that area was limited to a 2×6 grid. Using the accelerometer data, a visual representation was developed to compare impact characteristics at different impact locations. To achieve grid-based sensing with a minimal sensor count, four accelerometers were mounted in an inverted T arrangement across the chest plate (Fig. 3 left). The sensor positions were selected to maximise coverage while maintaining sufficient proximity for impact detection. Each sensor defined a primary sensing region around its mounting location, enabling impacts to be classified into discrete zones based on the relative magnitude and timing of the recorded peak acceleration.

To increase spatial resolution beyond the four discrete sensor locations, the impact surface was subdivided into a 2×3 grid, where the additional "virtual" grid cells were estimated using interpolation of neighbouring sensor responses. This approach was taken to allow impacts occurring between sensors to be approximated without increasing hardware complexity. This would produce a higher-resolution representation of impact transmission across the chest plate while maintaining a low-profile and wearable sensing architecture.

As the armour plate used was designed to protect players from impacts in football, the front-on shoulder tackle was chosen to simulate as it was identified as the most common, high impact tackle in Rugby and NRL [9]. To simulate this tackle within a laboratory environment, a weighted pendulum rig was used. Pendulum impacts were configured to approximate a scaled tackle energy by using an adjustable pendulum arm and impact head weight to achieve an impact energy of 35 J. The 4 sensors were mounted to the dummy torso (weighted boxing bag) using adhesive sports strapping tape 11cm apart (Fig. 3 left).

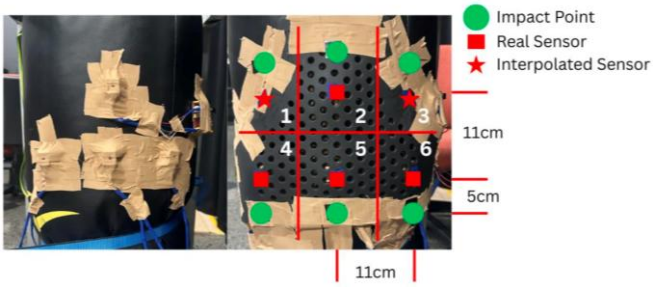


Fig. 3. Dummy torso with mounted sensors (left), and a six-section armour impact surface with a four-sensor array and labelled zones (right).

IV. Results

The absolute acceleration of the four accelerometers, in Zones 2, 4, 5, 6 (Fig. 3 right), were averaged over ten trials for impacts in each of the six zones. The virtual sensor Zones 1 and 3 were estimated from the peak values of the four physical sensors using the following algorithm:

(a) *if ((Zone 5 ⩾ Zone 2) && (Zone 5 ⩾ Zone 4)){*

Zone 1 = Difference between(Zone 2 ,Zone 4)}

else {

Zone 1 = Zone 4 + Zone 2 - Difference between(Zone 2 ,Zone 4)}

(b) *if ((Zone 5 ⩾ Zone 2) && (Zone 5 ⩾ Zone 6)){*

Zone 1 = Difference between(Zone 2 ,Zone 6)}

else{

Zone 1 = Zone 6+ Zone 2 - Difference between(Zone 2 ,Zone 6)}

The results plotted in Fig. 4 illustrate that the estimated Zones 1 and 3 displayed reasonable and expected dominance patterns corresponding to each impact. The limitation was that the predicted values for these estimated zones were consistently underpredicted when the estimated zone was the impact location. However, this still provides useful information, as it highlights the minimum value expected when that zone is impact location.

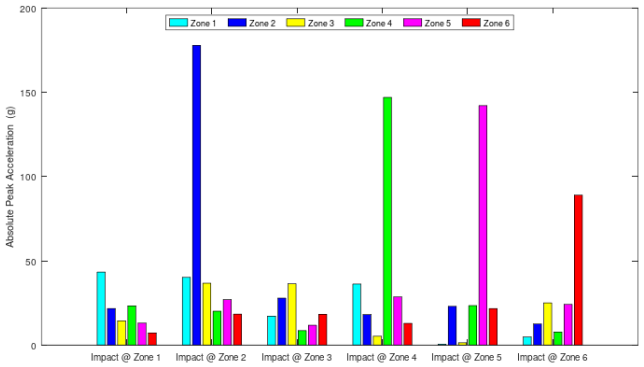


Fig. 4. Peak absolute acceleration across six impact zones. Virtual Zone 1 (cyan), Zone 2 (blue), Virtual Zone 3 (yellow), Zone 4 (green), Zone 5 (pink), and Zone 6 (red).

Fig. 5 presents a series of heat maps illustrating the normalised peak absolute acceleration distribution across the armoured surface for the impact tests at each of the six locations. Each map provides a clear visualisation of the detected impact location, the distribution of impact energy, and the relative dominance of each sensor zone relative to the total impact response. The maps were generated using the Octave '*contour*' function, with linear interpolation applied to estimate the values between the six measured points, creating a continuous heatmap effect.

The overlaid outlines show the Fempro Armour plate, the six defined zones, and the sensor locations and type. The impact points, indicated by green circles, were positioned 10 cm above each corresponding sensor in Fig. 5 (a), (b), (c), and (d), (e), (f) show them positioned 10cm below the sensor. The scale for each heat map was normalised to 1, representing the maximum peak absolute acceleration recorded for that specific impact. These plots confirmed that the sensor array configuration and the interpolation logic effectively identified and visualised the impact location and dominance across the entire armour surface.

V. Discussion

This work demonstrated that a custom high-g inertial sensing system can reliably capture and characterise short-duration, high-acceleration impact events relevant to torso contact in collision sports. Using the ADXL372-based sensing node, impacts were captured at a validated sampling

frequency of ~3200 Hz, enabling clear resolution of impact transients that are not adequately represented by general-purpose wearable IMU loggers. These results support the necessity of a high-range accelerometer architecture for measuring tackle-like collision events.

These results demonstrate that meaningful torso impact localisation can be achieved with minimal sensing hardware, supporting scalable deployment in wearable protective equipment.

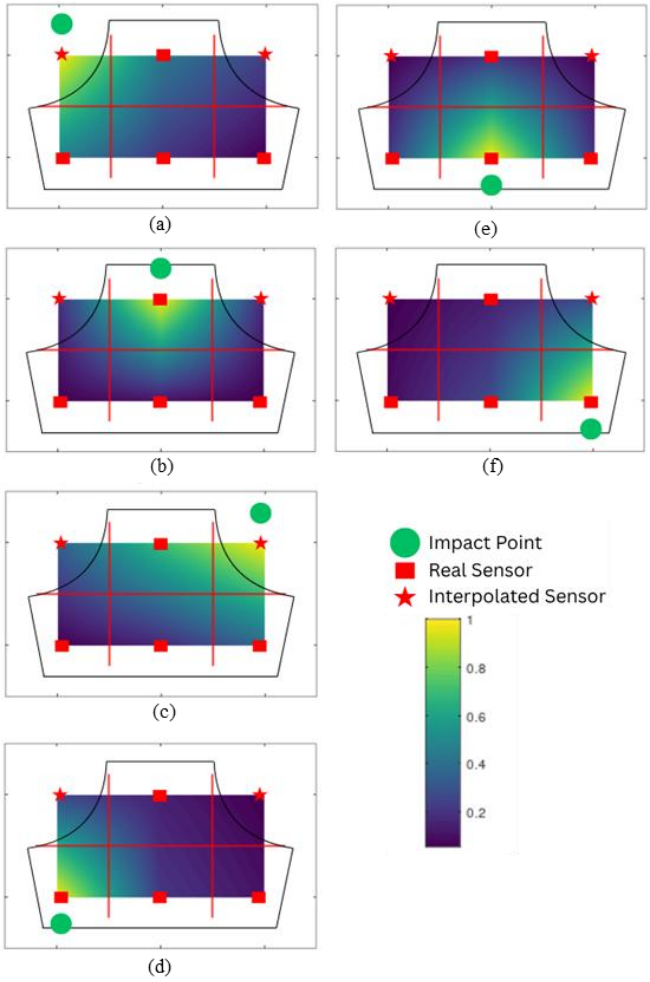


Fig. 5. 3×2 Sectioned heatmap for 6 impact simulation tests with overlayed armour position, impact zone 1-6 ((a)-(f) respectively)

Controlled pendulum testing further demonstrated that the proposed system can detect consistent impact signatures under repeatable laboratory conditions. The pendulum rig produced strikes at defined impact locations and energies, allowing systematic evaluation of sensor response across the armour surface. Across repeated trials, the sensor node provided stable peak response trends and distinguishable differences between impact sites, indicating suitability for laboratory-based impact characterisation and for future development toward wearable monitoring.

The observed variability in acceleration response at certain sites was primarily attributed to surrogate torso compliance and local surface properties, suggesting that future testing would benefit from improved surrogate stiffness control and anatomically representative substrates.

Experimental testing indicated that sparse sensor arrays can provide meaningful impact localisation while maintaining low hardware complexity. Despite the low resolution, the four-sensor configuration enabled subdivision of the armour into six regions. The interpolation-based estimation provided plausible responses for unsensed zones, although these were observed to underpredict peak acceleration compared to directly sensed zones. This suggests that while interpolation of the four sensors is suitable for producing qualitative "impact maps" at low resolution, more robust localisation may be required. This includes an increased sensor density, improved calibration of zone transfer functions, or learning-based localisation techniques trained on repeatable laboratory impacts.

Overall, the proposed high-g impact sensing system demonstrated strong capability for capturing tackle-like impact events without saturation and provides a practical, low-cost platform (< USD$150) for continued research into body armour impact monitoring.

VI. Conclusion

This study demonstrated a high-g, event-based inertial sensing system capable of detecting and localising short-duration torso impacts relevant to contact sports. A four-sensor accelerometer array reliably captured high-energy impacts without saturation and enabled spatial characterisation across an armoured chest surface using interpolation-based estimation. Laboratory pendulum testing confirmed consistent impact detection and effective visualisation of impact location and dominance. Overall, the findings highlight the suitability of high-range accelerometry for torso impact characterisation and provide a foundation for future development of miniaturised, wireless systems for in-field and longitudinal athlete impact assessment.

Future work should prioritise miniaturisation and packaging for embedded integration into armour plates, incorporation of wireless communication for in-field use, and expanded impact testing across a wider range of contact conditions and body geometries. This can be achieved through miniaturisation using custom-designed circuitry, leveraging the compact form factor and low power requirements of available components. Future work will also explore controlled variation of impact levels using the current pendulum setup.

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