Sensitive Non-invasive Acoustic Detection and Triangulation of Rib Fractures from Simulated Behind-Armour Blunt Trauma

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I. INTRODUCTION

The ability to accurately predict how, when, and where fractures will occur after impact could enhance injury risk assessments and improve injury countermeasures. Previous studies have mounted acoustic sensors directly to bone to determine initiation and location of initial microcrack fracture. The effect of the tissue disruption and the treatment of the bone to mount the sensors is unknown. This study uses non-invasive acoustic sensors placed in contact with skin, without being mounted to bone, to investigate rib fractures from simulated behind-armour blunt trauma (BABT) impacts. This research studies the initiation of a crack following impact. Testing included five cadaveric eviscerated porcine torsos in repeated impacts. The objectives were to determine fractures using the acoustic sensor signals and to locate where the fracture occurred using a multilateration algorithm.

II. METHODS

Eight acoustic hydrophone sensors (Teledyne Reson, Underwater Acoustics, Daytona Beach, FL, USA) were mounted onto the porcine skin, over the ribs, in a known position relative to the ribs (Fig. 1). Hydrophone sensors were selected because of their larger frequency band and durability in a biological environment compared to traditional acoustic emission sensors. To improve coupling between the sensors and the skin, ultrasound gel was applied. Using a gas gun, a projectile/indenter was accelerated towards the impact site at velocities intended to cause single rib fractures. Forty-seven impact tests to the left and right lateral mid-thorax were conducted. Data from acoustic sensors were collected at a frequency of 6 MHz. Video data from two high-speed cameras (Phantom V1212, Vision Research, Wayne, NJ, USA) were collected at a sample rate of 10,000 fps. The first acoustic emission times were determined from the sensor rising above eight times the sensor noise pre-test. To determine the estimated location of crack initiation and real-time fracture occurrence, multilateration was used for tests that had one or a limited number of macroscopic cracks. Using positional information from manual distance measurements and angle calculations (ImageJ, Java-based image processing programme), the sensors and impact location were registered to a single 2D projection. The multilateration algorithm used known sensor location coordinates, first acoustic emission times, initial peak voltage of sensor emissions, and the speed of sound through soft tissue to locate the initial fracture (Eq. 1). The unknowns were the location coordinate of the first fracture and the real-time fracture occurrence. The sum of the equation for each sensor was multiplied by the initial peak voltage, and the total sum was minimised, while the unknown distances were optimised.

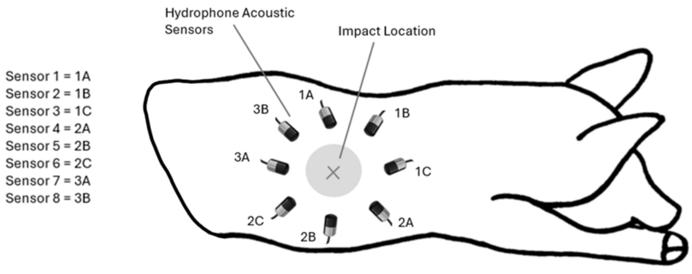

Fig. 1. Test set-up and sensor schematic. The positioning of the swine was on the edge of the table with its right side facing the impactor.

$$\sum_{i=1}^{8} V_i \times \left[(X_{Fracture} - X_i)^2 + (Y_{Fracture} - Y_i)^2 - \left(C \times (T_{known} - T_{unknown})\right)^2\right]^2 = Total\ Sum \quad (1)$$

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III. INITIAL FINDINGS

To help describe fracture locations, the ribs were numbered consecutively from top to bottom, beginning with the most superior rib as one. Using this nomenclature, most fracture localisations ranged from ribs seven to nine, aligning with the intended shot location centred around the eighth rib. The multilateration results provided an estimate of the first fracture locations. Effects from rib thickness, length, curvature, and the thickness of sensors were considered. Since precise locations of the sensors relative to the ribs in the X-ray images could not be easily determined; the precision of the method was used to assess its quality. Physical observations and X-rays confirmed the results in all tests. In some tests, ribs had multiple fractures and microfractures. For these tests, the algorithm localised to the same fracture location, regardless of signal combination.

2A. 2B.

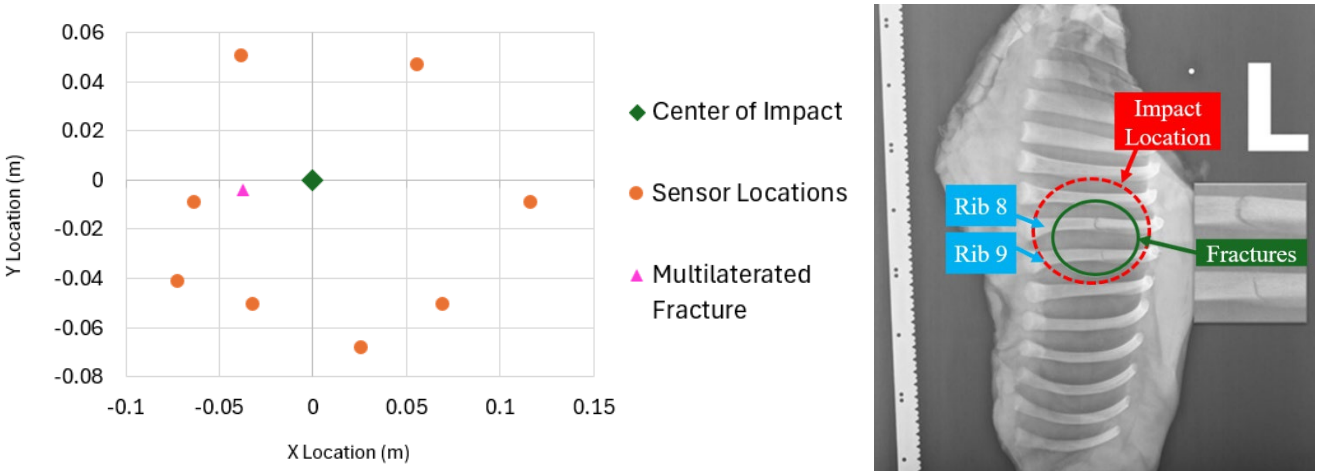

Fig. 2. A: an example of the multilateration results of the initial fracture location. Pink Triangle represents the fracture located at (-0.0373, -0.00412) from the centre of impact (0,0), represented by the Green Diamond. Orange Circles represent the hydrophone sensor locations. The localised initial fracture was on rib nine, near the centre of impact. B: x-ray confirming a transverse fracture on rib eight and a hairline on rib nine. The red chequered circle represents the location of the impact.

IV. DISCUSSION

This study demonstrates an approach for fracture detection using non-invasive acoustic sensors. The oscillations in the fracture, formed at the highest point of stress, produce a sound that was detected by the sensors. As the fracture progressed, the acoustic emissions increased, which provided a detailed signature of fracture progression. The sensors closer to the fracture origin detected the signal sooner than those farther away. The delay between the real-time fracture occurrence and time the sensors picked up data was due to the fracture's oscillations travelling through soft tissue at an estimated velocity of 1540 m/s [1]. For most impacts, the first fracture occurred under the shot location. After dissection, it was observed that a few subjects had a hairline fracture on the rib directly under the impact location, but the algorithm identified the first fracture, an oblique nondisplaced fracture, on a different rib. It is possible that the signal of the hairline fracture under the impact location did not exceed the threshold, or it could have been pre-existing since the swine witnessed multiple impacts. The multilateration algorithm provided accurate localisation of fractures, showing potential in injury biomechanics. However, the algorithm is limited to identifying only the first fracture, as it cannot isolate microfractures due to overlapping signals. Due to the limitations of X-rays, not all microscopic fractures can be detected [2], which is why palpating for displacement on the rib surfaces was necessary for accurate results. The size of tissue thickness affects fractures and velocity speed. Skin thickness measurements were not obtained, so they could not be factored into the multilateration process. Despite these limitations, this method of multilateration shows promise for improving non-invasive injury diagnostics in any injury context. This algorithm could be used as a tool to address where the most common places of fracture take place, helpful in sports injuries and injury biomechanics research to understand injury mechanisms.

V. REFERENCES

[1] Fieldman, M. K., *et al.*, *Radiographics*, 2009.
[2] Pinto, A., *et al.*, Pubmed, 2018.