XSENSOR High-Speed Impact System in PMHS Thoracic Impact Testing

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ABSTRACT

The goal of this testing was to use the XSENSOR High-Speed Impact System in a series of PMHS thoracic impacts to investigate the sensors potential to predict thoracic injury and response to blunt loading. This testing was completed with a single PMHS who fit the 50th percentile male criteria for age, weight, BMI, and also had a "normal" aBMD score. A series of seven thoracic impacts were conducted which included: impacts to the front, left, and right aspects, two different impactor faces and two different energy levels. Findings from each test focused on comparing the dynamic pressure profiles of the impact area to the recorded strains from the attached gages on each rib, and also to any injury locations that were documented during autopsy. The timing of each fracture, as determined from the strain gages, were also compared to the timing of the peak pressures from the XSENSOR output in each given region of interest. The pressure maps revealed that the XSENSOR High-Speed Impact System was able to identify the thoracic areas that contained fractures and additionally the timing of the peak pressures correlated to the predicted timing of fracture from the strain gages. A limitation of the testing was that a single PMHS was impacted multiple times in order to collect a large quantity of comparable data between instrumentation techniques. Also, while the conducted impacts did mimic historical thoracic impact tests, the tests were performed under very basic boundary conditions. Given the findings from this laboratory setting, it appears that the XSENSOR High-Speed Impact System has the ability to map pressure distributions during dynamic impacts that could help to identify injuries in blunt high impact scenarios.

INTRODUCTION

In 2019, there were approximately 36,096 fatalities and 2,740,000 injuries due to traffic crashes [4]. Up to 35% of trauma-related deaths are thoracic trauma in the United States, with the most common cause of blunt chest trauma being motor vehicle collisions, which account for up to 80% of these injuries [1]. Although thoracic injuries have been studied over the years, these injuries are still relevant and continue to occur today. Understanding the thorax and the way it interacts with vehicle safety structures will allow researchers to continue to improve occupant safety and offer better protection in motor vehicle crashes.

Historically, studies have been done in order to understand injury threshold of the thorax, and to reduce thorax injury. A few key studies have been conducted, including Oblique and Lateral Testing conducted by Shaw et al. (2006), Oblique and Lateral Testing conducted by Rhule et al. (2011), and Frontal Fixed Back testing conducted by Murach et al. (2018). All three of these studies provided data and insight into the thorax and how it responds to different impact scenarios, but also revealed how much more data is needed in order to better define thoracic biofidelity for all occupants.

Shaw et al. (2006) characterized PMHS thoracic response to blunt impacts in oblique and lateral directions through pendulum impact tests. Past research combined oblique and lateral data, considering them similar. It was determined that defining the biomechanical response of the thorax to oblique impacts was important in side impact car crashes where the crash loading can often be anterior-oblique in direction. This study consisted of two low energy impacts on each of seven subjects at 2.5 m/s, each with one lateral and one oblique impact to opposite sides of the PMHS. Results of this study showed that force and deflection for oblique thoracic response in low-speed impacts was found to be different than lateral thoracic response, contrary to what previous studies had shown [3].

Rhule et al. (2011) wanted to test the findings from Shaw et al. (2006), but with higher impact speeds, in order to assess whether lateral and oblique responses are different (as observed by Shaw et al. (2006)), or similar (as observed by ISO 9790). This study consisted of twelve PMHS which were impacted by a pneumatic ram with a rectangular face plate at the level of the xyphoid process, in either the pure lateral or 30° anterior-to-lateral oblique direction. It was determined that these responses demonstrated similar characteristics for both the lateral and oblique impacts, which indicated that it may be reasonable to combine lateral and oblique responses together at these higher speeds to define thorax response. This study also found that these tests conducted indicated that less chest compression may be required in order to obtain serious thoracic injury in oblique impacts as compared to lateral impacts at these higher speeds of 4.5 or 5.5 m/s [4].

Murach et al. (2018) focused on understanding rib properties in relation to an intact thorax. The aim of this testing was to understand this relationship by creating a transfer function between an individual rib and thorax. This study consisted of six PMHS in a series of non-injurious fixed-back frontal impacts at low-speeds, with each being tested in four tissue states: intact, intact with upper limbs removed, denuded, and eviscerated. Each impact was conducted with a rectangular impactor face, with the goal of testing to be analyzing thoracic response in a low-speed repeatable set-up. After testing the eviscerated thorax, eight individual mid-level ribs were taken from each PMHS and loaded to failure. The findings of this study showed that the rib model did not properly predict the eviscerated thoracic response, however they did help to provide a better understanding of the influence of the connective tissues on a rib and its behavior in the thorax [2].

These past thoracic studies relied on instrumentation and technology like chestbands, strain gages, accelerometers, and VICON motion tracking systems to define the biofidelic response and injury threshold of the thorax to blunt impacts [2-4]. All instrumentation has strengths and weaknesses, but a common weakness across these examples is that they sense the loading at a single point, or in the case of the chestband, at a single cross-section of the thorax. This limitation does not allow researchers to understand how the thorax as a whole is interacting with the impacting surface.

The XSENSOR High-Speed Impact system (XSENSOR, Calgary, Canada) is technology that records the pressure profiles of a system over time and produces a pressure map of the distributions of the system during a dynamic event. This technology has been used in an array of different applications, with one example of this being to test occupant safety equipment to determine the pressure profile during a crash pulse and the pressure at peak acceleration. Due to the versatility of this technology, it allows researchers to use it to better fit their needs in other scenarios, or example recording pressure profiles of an impacting load to a broad area like that of the thorax.

The goal of this research was to use the XSENSOR High-Speed Impact System in a series of PMHS thoracic impacts to investigate the potential of the XSENSOR system to measure thoracic response to blunt loading and to potentially identify thoracic injury. The test series conducted mimicked the test boundary conditions of past thoracic research conducted in the Injury Biomechanics Research Center (IBRC) [2-4].

METHODS

This testing was completed with a single PMHS which fit the 50th percentile male criteria for age, weight, BMI, and had a "normal" aBMD score. The PMHS was made available through The Ohio State University's Body Donor Program and all applicable Body Donor Program and University guidelines were reviewed and followed. A 50th percentile male was selected in order to represent the occupant population that was used in previous studies.

Instrumentation for the impact series included a mix of strain gages to determine fracture timing, 6DX blocks to measure spinal kinematics, and a XSENSOR pressure pad (10"x10") to measure the pressure profile during each impact. The location of the strain gages and 6DX blocks can be seen in Figure 1, with strain gages represented by the blue, and 6DX blocks represented by the red markings. Strain gages were located on the sternum along with both an anterior and an anterior-oblique location on ribs 2-8 on both right and left sides. The 6DX motion blocks were placed on the manubrium, 1st thoracic (T1), 4th thoracic (T4), 12th thoracic (T12), and 1st sacral (S1) vertebral levels, and the XSENSOR pad location varied between tests, but was placed over the thoracic region of interest. The impactor was instrumented with a 6-axis load cell behind the impactor face to measure the applied load, a linear potentiometer on the ram to measure displacement of the ram, and accelerometers to calculate impact speed.

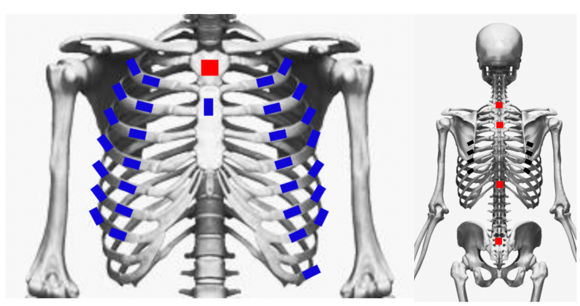

Figure 1: Instrumentation Locations.

The series of impact tests conducted on the PMHS were based on previous impact testing conducted in the IBRC, which used different instrumentation techniques and thus potential for comparison between XSENSOR and traditional measurement techniques [2-4]. The PMHS was seated in an upright position, with the arms raised until they were approximately parallel to the ground in order to prevent impactor interaction with the arms of the PMHS and to ensure the thoracic cage was not raised (Figures 1-3). A series of seven thoracic impacts were conducted including: impacts to the front, left, and right aspects of the thorax, two different impactor faces and three different energy levels. The test matrix, including the testing order and boundary conditions used for each impact, is shown in Table 1. Figures 1-3 show different PMHS placements depending on the different impact aspect that was being tested, with Figure 1 showing a frontal impact, Figure 2 showing a lateral impact, and Figure 3 showing an oblique impact.

Figure 1: Impact 01 Set-up.

Figure 2: Impact 02 Set-up.

Figure 3: Impact 03 Set-up.

Table 1: Test Matrix

	Impact 01	Impact 02	Impact 03	Impact 04	Impact 05	Impact 06	Impact 07
Impact Aspect	Frontal	Lateral	Oblique	Lateral	Lateral	Oblique	Lateral
PMHS Side	-	Left	Left	Left	Right	Right	Right
Impactor Face	Rectangle	Rectangle	Circle	Circle	Rectangle	Circle	Circle
Speed (m/s)	2.16	2.56	2.49	4.54	2.52	2.52	4.43
Rib Fxs	Right 5	-	Left 3, 4, 5	Left 6, 7	-	Right 4, 6, 7	-

All data was collected using a SlicePro (DTS, Seal Beach, CA) data acquisition system at the sampling rate of 20,000 Hz. Event tape was placed on the impactor face and the thorax, which helped define time zero for each impact as the time of contact between the thorax and the impactor face. All data was processed in MATLAB, and strain rate and along with micro-strain were plotted versus time. The impact velocity of the ram was calculated through both a light trap and an accelerometer. Both methods provide an impact velocity of the system in order to show how fast the impactor ram is traveling during the testing series.

RESULTS

The results of the impacts were analyzed, and fractures were identified by using both the strain and strain rate plots that were calculated in MATLAB from the strain gages placed on the ribs. A sudden, sharp drop in strain helped to identify a fracture, and a summary of the rib fractures which occurred during the seven impacts can be found in Table 1. These fracture locations that were found through strain graphs were then compared to actual fracture location during autopsy to ensure the fracture locations were aligned, and a diagram of those locations can be seen in Figure 4. Overall, nine fractures were found over the duration of the impact study, and a diagram of each fracture locations can be seen in Figures 6 through 14.

These fractures were then compared to the pressure maps from XSENSOR during the time of fracture. The gradient color key can be seen in Figure 5, where areas of red indicate the highest-pressure areas, and areas of dark blue represent the lowest-pressure areas. Figures 6 through 14 show each fracture that occurred, the corresponding pressure map at the time of fracture, and the fracture location (indicated via a red "x") on the PMHS. The XSENSOR pressure map still photos reveal the corresponding pressure across the front of the thorax at the exact time at which the rib fractured.

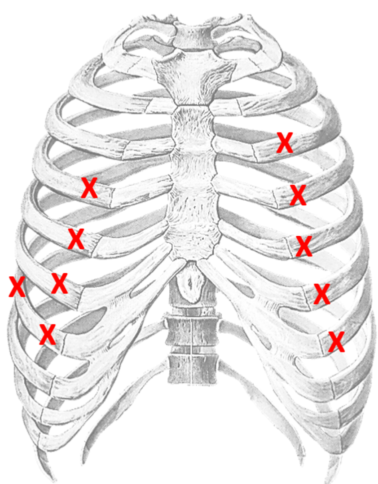

Figure 4: Map of Fracture Locations.

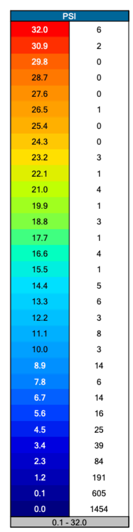

Figure 5: XSENSOR Scale.

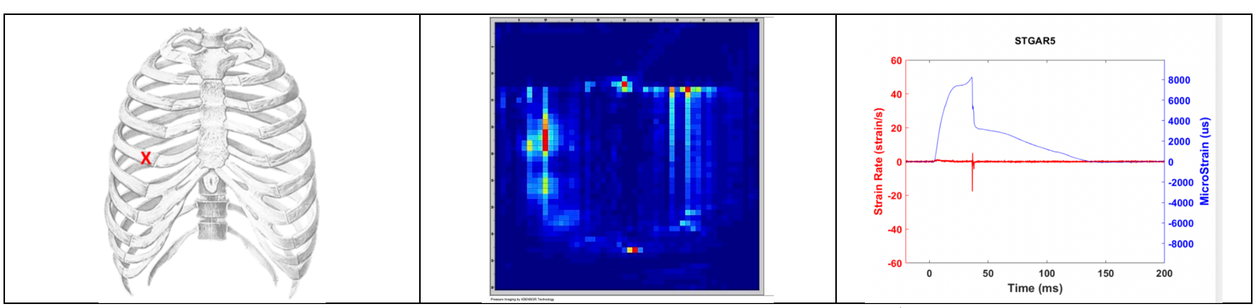

Figure 6: Impact 01 – Fracture occurred at 36 ms to 5th Right Rib.

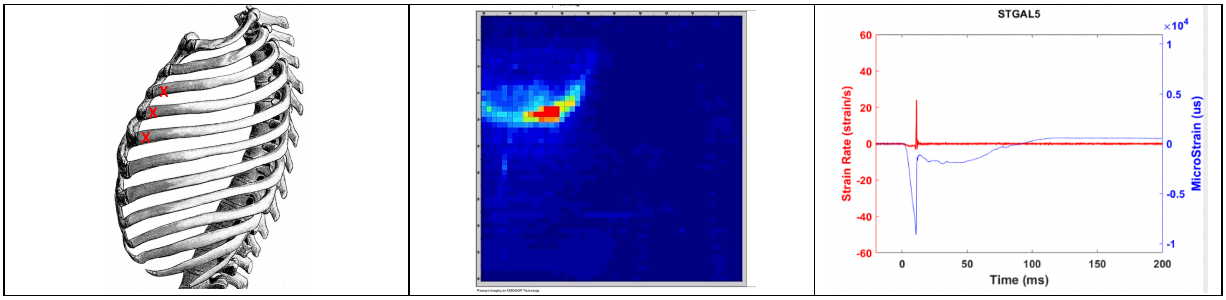

Figure 07: Impact 03 – Fracture occurred at 25 ms to 5th Left Rib.

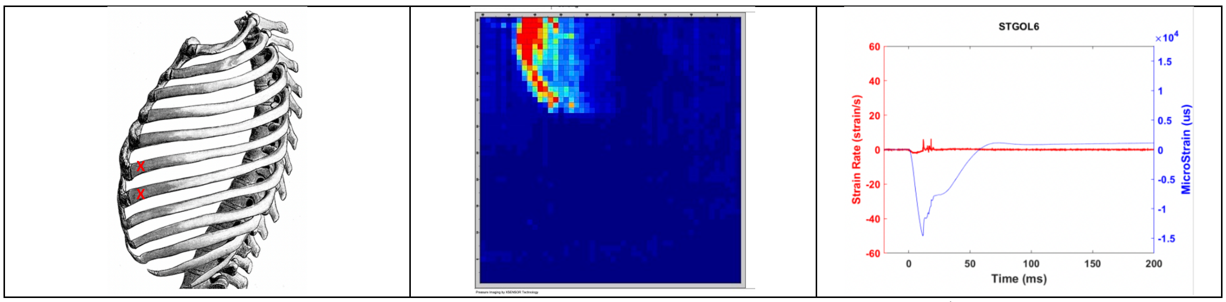

Figure 08: Impact 04 – Fracture occurred at 11 ms to 7th Left Rib.

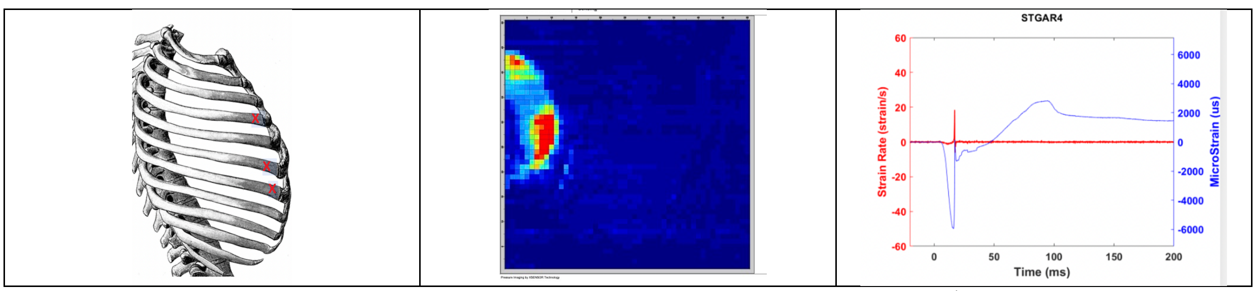

Figure 09: Impact 06 – Fracture occurred at 17 ms to 4th Right Rib.

DISCUSSION

Findings from each impact focused on comparing the dynamic pressure profiles of the impacted thorax to the recorded strains from the attached gages on each rib, and to any injury locations that were documented during autopsy. The timing of each fracture, as determined from the strain gages, were also compared to the timing of the peak pressures from the XSENSOR output in each given region of interest. The pressure maps revealed that the XSENSOR High-Speed Impact System identified that the highest-pressure areas were aligned with the anatomic locations of the resulting fractures, with Impact 04 being the outlier. For Impact 04 the fracture locations do not perfectly align with the high-pressure areas, due to the face that ribs 3, 4, and 5 broke during the previous impact (Impact 03), which caused these ribs to deflect. This caused the posterior portions of ribs 6 and 7 to then be loaded and transmitted the forces to the anterior aspect where they broke. In addition, the timing of the peak pressures correlated to the predicted timing of fracture from the strain gages. For each instance of fracture, the corresponding pressure maps show high pressure during the time of fracture, and within the same area of fracture, with some instances even showing an outline of the shape of the impactor face. It is important to note that these conducted tests did match the historical PMHS impacts from a spinal kinematics standpoint.

One limitation of the testing conducted was that a single PMHS was impacted multiple times to collect a large quantity of comparable data between instrumentation techniques. In order to improve data, more testing could be done with a greater number of subjects in order to provide more data and insight into thoracic response. Also, while the conducted impacts did mimic historical thoracic impact tests, the tests were performed under simplified boundary conditions compared to motor vehicle crash scenarios. One area of improvement to consider in future PMHS testing with the XSENSOR system is to conduct a CT on the PMHS following the placement of the XSENSOR pad to obtain exact anatomical positioning coordinates of the pad instead of having to rely on x-rays. This would allow for more accurate results and ensuring the placement of the pad is consistent among tests. Also, further investigation should be conducted with the XSENSOR High-Speed Impact System in a dynamic sled environment to test the system's durability and ability to document interaction between a PMHS and typical safety devices.

CONCLUSIONS

Given the findings from this laboratory setting, it appears that the XSENSOR High-Speed Impact System has the ability to map pressure distributions during dynamic impacts that could help to identify injuries in blunt high impact scenarios. The XSENSOR pressure maps showed high pressure areas that aligned anatomically with the fracture locations and showed high pressure areas at the exact time of fracture.

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