OBLIQUE AND LATERAL IMPACT RESPONSE CHARACTERISTICS OF A DENUDED PMHS THORAX

A Thesis

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By,

Geoff Brown

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The Ohio State University

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Honors Examination Committee:

Dr. John Bolte, IV, Advisor

Dr. James Schmiedeler

Approved by

Advisor
Department of Mechanical Engineering

Abstract

Thoracic trauma is directly responsible for 25% of all trauma related fatalities and indirectly contributes to another 25%. Since most thoracic trauma is caused by automobile crashes, the need for accurate data regarding thoracic impact grows continuously as more and more cars are on the road. Many of these automobile crashes are side impacts, which lead to a primary direction of force on the person inside to be oblique and anterior to lateral. The purpose of this project is to determine the response of a denuded human thorax to oblique and lateral blunt force impacts. Specifically the project will focus on the linear and rotational stiffness characteristics of a denuded post-mortem human subject (PMHS) thorax. There is a lack of data regarding anterior oblique and posterior oblique thoracic impact response characteristics and this project will focus on obtaining the response of the PMHS thorax to these types of impacts. The current impact tests and anthropomorphic test devices (ATDs) account for frontal and lateral direction crashes only. Response in the oblique direction was previously assumed to be similar to lateral responses, but new research has shown that this may not be the case.

This project consisted of both designing the fixture to be used to support the thorax during testing as well as the experimentation and analysis of the results. The thoraces were obtained from fresh post-mortem human subjects and all research was done at the Injury Biomechanics Research Laboratory (IBRL). The data from this project will be used in conjunction with results from other projects at the IBRL in order to determine a more accurate definition of the biomechanical response of the human thorax during a vehicle crash. This data can then ultimately be used to create a new anthropomorphic test dummy thorax for use in crash testing.

Dedication

Dedicated to my friends and family who were always there to provide support. Without them I never could have completed this research.

Vita

August 29, 1985…………………………………….……………………Born- Hamilton, Ohio

Fields of Study

Major Field: Mechanical Engineering

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1. Introduction

Thoracic trauma is directly responsible for 25% of all trauma related fatalities and indirectly contributes to another 25% [1]. Since most thoracic trauma is caused by automobile crashes the need for accurate data regarding thoracic impact grows continuously as more and more cars are on the road. There are different types of injury mechanisms that can occur due to blunt force thoracic trauma. At low speeds (less than 5 mph) the main injury mechanism is the crushing of the rib cage causing compression of the organs [2]. This type of injury leads mainly to bruising of the organs and also fractures to the rib cage. At higher speeds (5 mph to 30 mph) the injury mechanism is still compression, but it is accompanied by shear and tensile loading. This can cause significantly more threatening injuries including aortic rupture [2, 3].

Currently the main type of test that is used to simulate the impact of an automobile crash is a sled test where a crash dummy is subjected to a blunt force impact of similar magnitude to an actual accident. The current impact tests and anthropomorphic test devices (ATDs) account for frontal and lateral direction crashes only. However, during a side impact accident the primary direction of force is oblique in the anterior-lateral direction as shown in Figure 1. Response in the oblique direction was previously assumed to be similar to lateral responses, but new research has shown that this may not be the case [1, 4]. The IBRL is currently working on developing a new sled test that will subject a dummy to anterior oblique blunt force impact. However, for the results of these tests to be interpreted correctly in the future the actual response of a human thorax subjected to these types of loads must be determined.

Previous work at the IBRL has already shown a discrepancy between the biomechanical thoracic response of lateral and anterior-oblique loading [4]. Further study is needed however, to accurately determine the directional dependence of the biomechanical thoracic response. While oblique impact produces fewer serious injuries and fatalities than non-oblique impact [5], determining exactly what causes the difference is vital to produce more accurate test results in the future.

For this study, thoraces obtained from PMHS were mounted on an apparatus that allowed for different loading configurations. The mounting apparatus must support the thorax for use with frontal, lateral, and oblique impacts as well as torsional loading in order to determine the respective response characteristics. A series of accelerometers, load cells, and rotational velocity sensors were attached to the ribs of the thoraces in order to analyze the resulting stiffness characteristics of the varying applied loads.

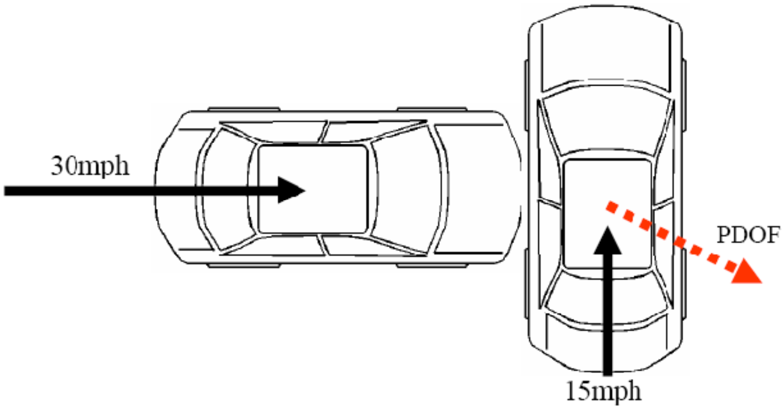


Figure 1: Primary Direction of Force during Side Impacts [4]

2. Anatomy

The thorax is the region of the body that lies superior to the diaphragm, inferior to the neck, and inside the shoulders. The thorax is formed by 12 ribs, the sternum, costal cartilages, and 12 thoracic vertebrae [6]. All of these structures are shown in Figure 2 below.

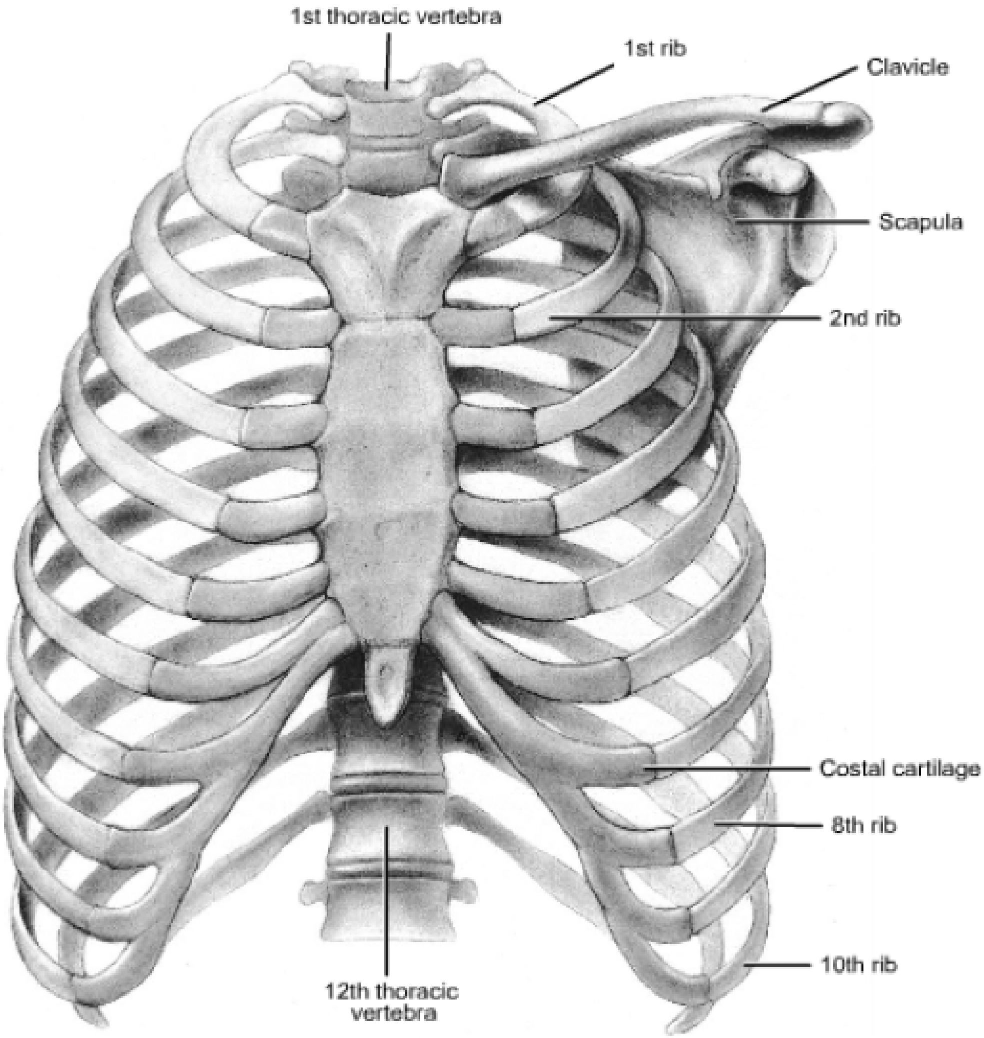


Figure 2: Anterior View of Thoracic Skeletal Structures [6]

The skeletal structures shown in Figure 2 form the rib cage. The rib cage has the function of housing the internal organs of the thorax including the heart and lungs. Also the rib cage serves to provide an attachment for the muscles of the neck, back, shoulders, and abdomen.

The vertebral column connects the head and neck to the superior aspect of the thorax and connects the pelvis to the inferior aspect of the pelvis. The vertebral column is composed of seven cervical vertebrae (C1-C7), twelve thoracic vertebrae (T1-T12), and five lumbar vertebrae (L1-L5) [6]. The thorax contains only the 12 thoracic vertebrae.

The ribs attach to the vertebrae on the transverse processes. This joint is a fibrous joint and provides much more support than the attachment to the sternum. The sternocostal joints (joints between ribs and sternum) are mostly synovial joints and allow for much more articulation than the joint between the ribs and the vertebrae. The relations between the two joints can be seen in Figure 2 and Figure 3.

Ribs 1-7 are called true ribs, because they articulate with both the spine and the sternum. Ribs 8, 9, 10 are called false ribs because they do not articulate with the sternum, but instead with the costal cartilage that bridges the gap between these ribs and the sternum. Ribs 11 and 12 are called floating ribs because they only articulate with the vertebrae and not with the sternum at all.

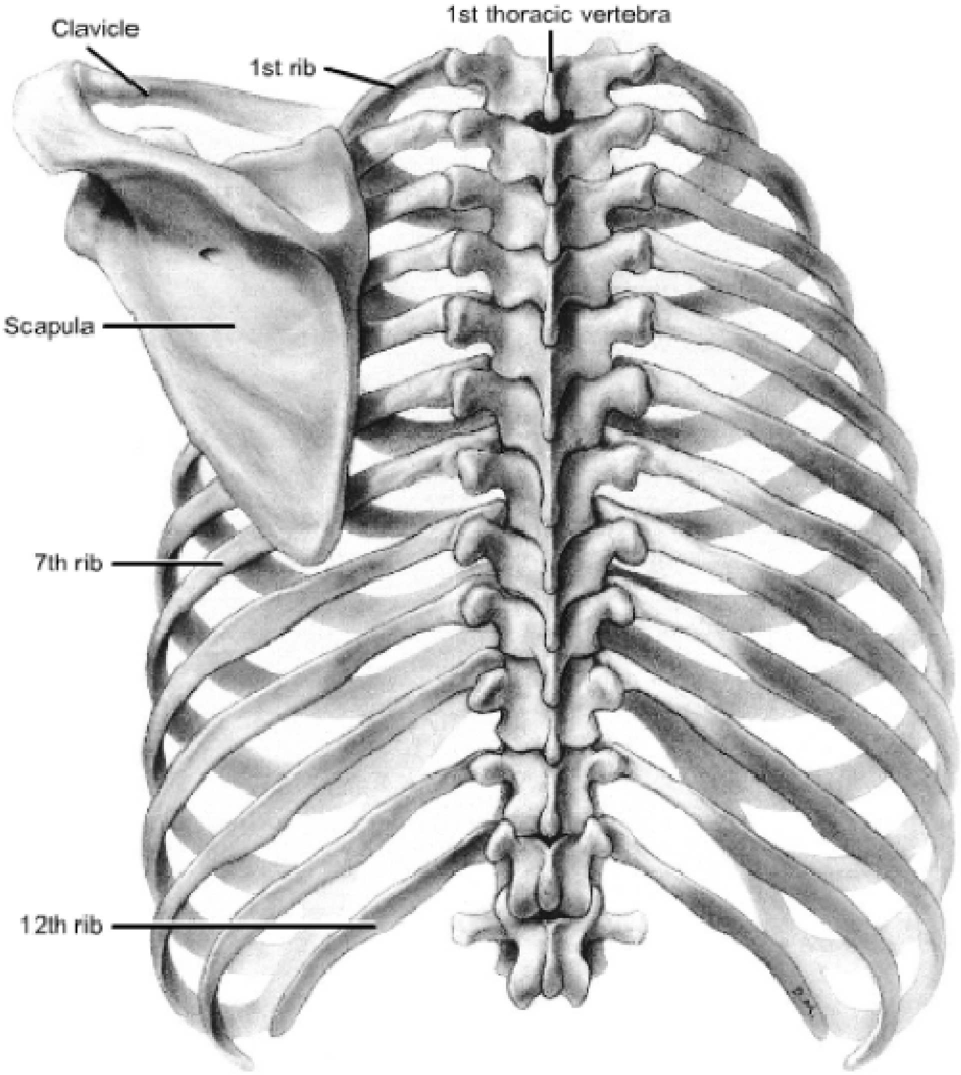


Figure 3: Posterior View of Thoracic Skeletal Structures [6]

3. Background

a. Studies completed prior to 2006

There has not been mush research done specifically to determine the directional response of the PMHS thorax. Many of the studies done before 2006 were conducted using sled tests. Sled tests are designed to simulate the impact and loading of a side-impact automobile accident. The first work was done by Kallieris et al. in 1981 [7] . Kallieris performed many different impacts at many different speeds and wall stiffness parameters. The result was a lot of data of different types such that only general conclusions about the biomechanical response of the thorax could be determined.

Marcus et al. [8] pooled sled test data from many different researchers in 1983 in order to attempt to draw conclusions about the response of the thorax. The problem, however, was that since the data was pooled from so many different people there were many different test configurations. Also, many of the tests resulted in multiple fractures. These limitations prevented a specific response of the thorax from being determined.

Cavanaugh et al. [9, 10] performed two different studies. The first study included side impact sled tests from 12 subjects. The second study also used side impact sled testing, but 18 subjects were used. In both studies no subject sustained less than 13 rib fractures. The high amount of fractures prevented a response of an intact thorax from being determined.

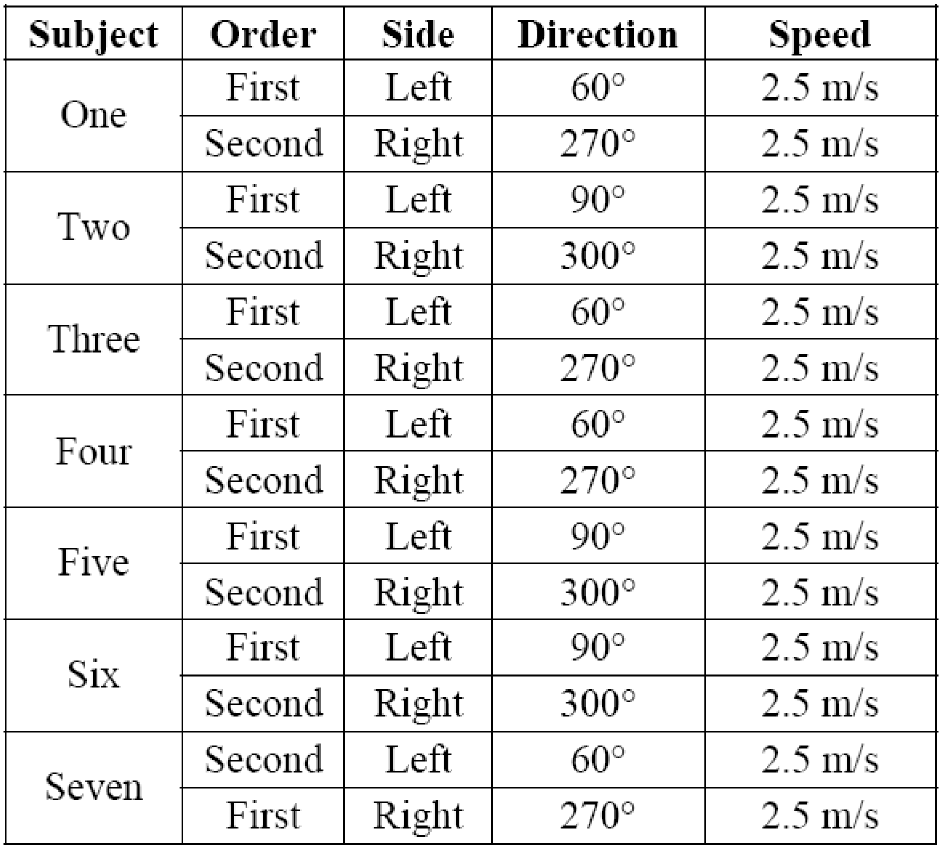
All of these studies [7, 8, 9, 10] used sled tests to try and determine the response of the thorax. The problem inherent with sled testing is that the arms prevent direct thoracic impact.

Instead, the wall impacts the subject's arm first and the force is transmitted to the thorax indirectly. The solution to this problem is to impact the thorax directly by conducting a pendulum test. A pendulum test keeps the subjects arms raised during impact and allows for direct thoracic impact. Before 2006 there were only two studies conducted that used pendulum tests for thoracic impacts. Eppinger et al. in 1984 [11] and Viano in 1989 [12] both conducted pendulum tests. Eppinger et al. conducted four lateral impact pendulum tests, but did not use the data to characterize the response of the thorax. Viano [12] performed 16 pendulum tests at a range of speeds from 3.6 m/s to 10.2 m/s. Viano concluded that the peak forces exerted on the thorax in the lateral and oblique directions were of the same magnitude and thus data from the two different impact directions could be compared or combined.

b. Shaw et al. 2006

In 2006 Shaw et al. [4] used pendulum testing to attempt to characterize the response of the thorax. Shaw used 7 subjects and performed one lateral impact and one oblique impact per subject. Also, each impact was conducted on different sides of the subject. For example, for subject O-T0503 the oblique impact was on the left side and the lateral impact was on the right side. The test matrix used by Shaw is shown in Table 1. A pre-test view of the orientation of the subject can also be seen in Figure 4.

Table 1: Shaw et al. test matrix [4]



Subject	Order	Side	Direction	Speed
One	First	Left	60°	2.5 m/s
	Second	Right	270°	2.5 m/s
Two	First	Left	90°	2.5 m/s
	Second	Right	300°	2.5 m/s
Three	First	Left	60°	2.5 m/s
	Second	Right	270°	2.5 m/s
Four	First	Left	60°	2.5 m/s
	Second	Right	270°	2.5 m/s
Five	First	Left	90°	2.5 m/s
	Second	Right	300°	2.5 m/s
Six	First	Left	90°	2.5 m/s
	Second	Right	300°	2.5 m/s
Seven	Second	Left	60°	2.5 m/s
	First	Right	270°	2.5 m/s

Figure 4: Pendulum Test -- Pre-test view [4]

Shaw used these tests to show that there is a difference between the responses of the thorax under loading in different directions. Figure 5 shows the pre-test and post-test chest contours obtained by Shaw. These contours were obtained using a chest band that has 40 accelerometers equally spaced along its length. The chest band is used mainly for localized deflection results.

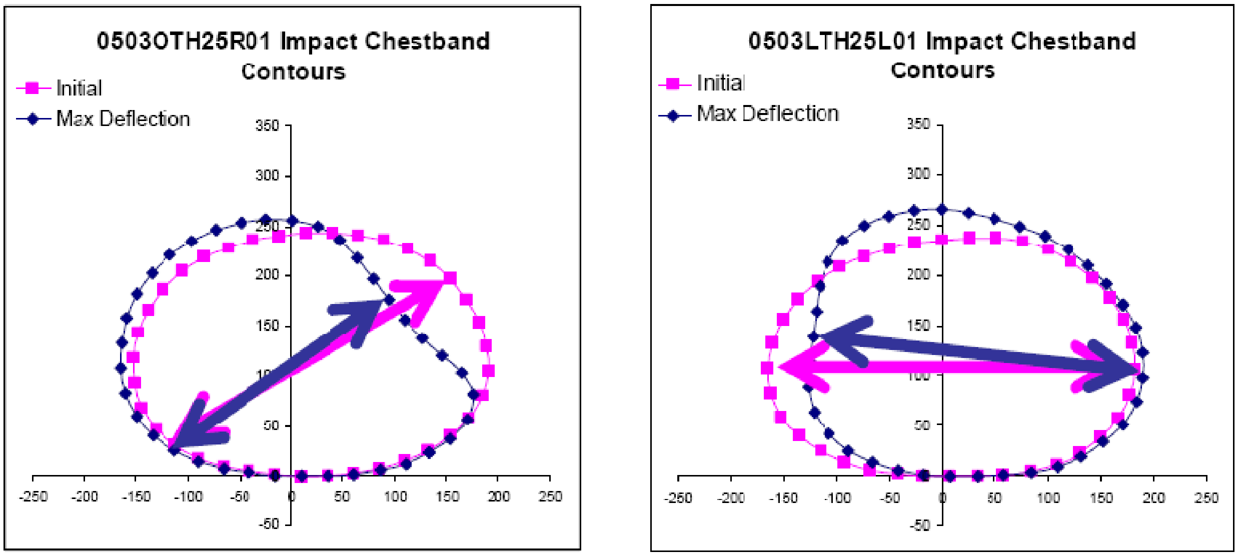


Figure 5: Oblique and Lateral Chest Band Contours [4]

Figure 5 shows that the thorax responds differently when impacted form different directions. When impacted obliquely, there is more localized deflection and less rigid body motion than in the case of lateral impacts. Figure 5 also shows that during a lateral impact the sternum moves in the anterior direction, but during oblique impacts this movement is less significant.

Figure 6 shows the force versus deflection corridors for both the oblique and lateral impacts. The shaded areas represent the corridors and the dark black lines represent the averages of all the tests.

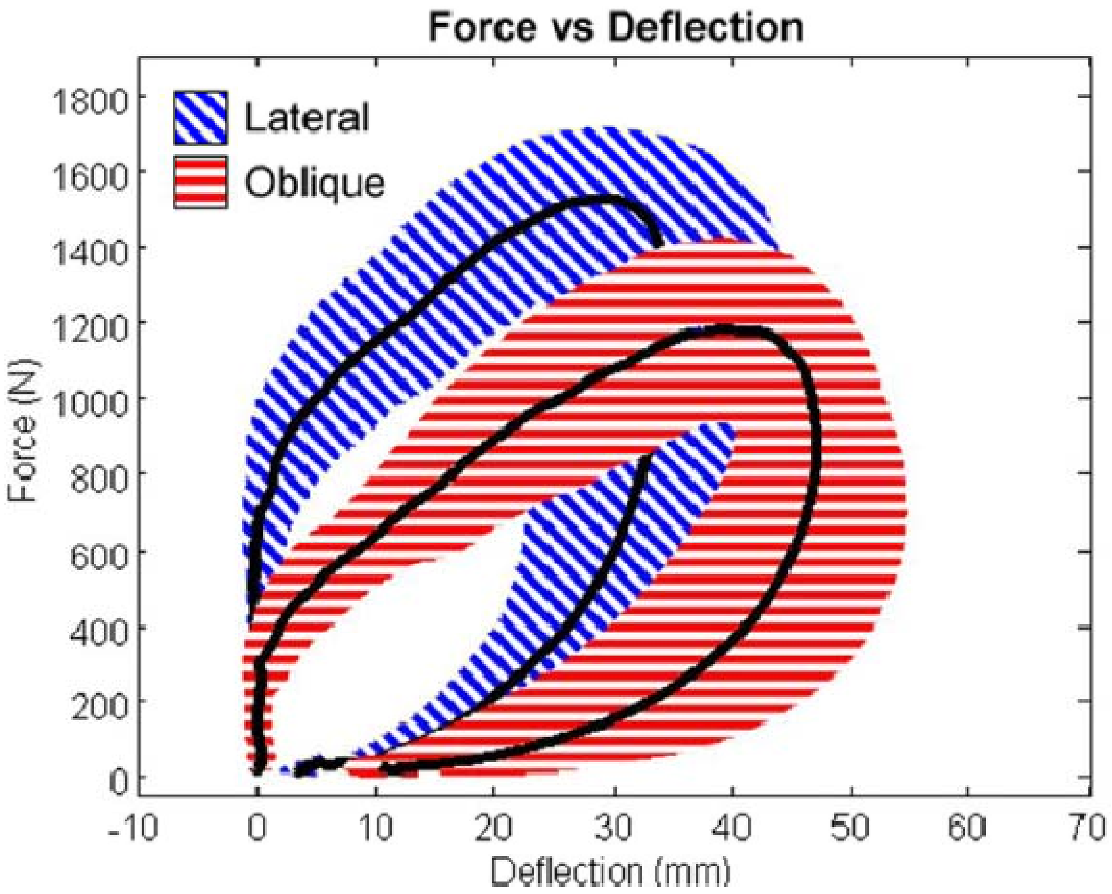


Figure 6: Force vs. Deflection Corridors for Oblique and Lateral Impacts [4]

From Figure 6 it is easy to see that the thorax is more compliant in the oblique direction than in the lateral direction. For a given force, the thorax deflects more in the oblique direction than the lateral direction. Shaw also concluded that the average impact force in the lateral direction (1562 N) was larger than the average force in the oblique direction (1229 N).

4. Fixture Design

This chapter is divided into three sections. The first section explains the design conditions that were considered during the design of the fixture. The second section will discuss the initial design that was used for the first test subject. The third section will show the design changes that were made after the first subject test and before the second subject test. Technical drawings of all parts of the fixture can be found in the appendix.

a. Design Conditions

- Fixture must be able to support a denuded PMHS thorax
    - Attachment to spine of thorax
- Optional sternum support must be able to restrict rotation about vertical axis
    - Can be excluded for tests where rotation is desired
- Fixture must rotate to allow for change of angle of impact

b. Initial Design used for first test

Figure 7 shows the 3D model of the fixture in its assembled form. The base of the fixture is 24 inches square. This size was chosen based on the size of the lift table that the fixture was placed upon. There are three separate hole patterns drilled and tapped into the base of the fixture. The three hole patterns are for the two support struts (one pattern each) as well as the sub-base of the fixture. The patterns are drilled so that the base can remain fixed to the table and the rest of the fixture can be rotated from -15 degrees (oblique and posterior to lateral) to 30 degrees (oblique and anterior to lateral) in 15 degree increments. Setting the fixture at 0 degrees allows for a lateral impact, while rotation in either direction allows for different oblique impacts. All pieces of the fixture are made from 0.5 inch thick, T6061 grade aluminum unless otherwise noted. T6061 aluminum was chosen due to its corrosion resistance, high stiffness to weight ratio, ease of cleanup, and welding properties. While most of the fixture is secured using ¼-20 threaded bolts, there are welds that were unavoidable in designing the support struts.

The vertical plate is used to directly mount to the spine of the thorax. The plate is 27” tall by 4” wide. The width was chosen so that upon deflection/rotation of the thorax the posterior aspect of the ribs would not contact the fixture and restrict movement. There are 3 columns of holes and 22 rows of hole in the array. The rows are spaced 0.75” apart to accommodate smaller thoraces and there are enough rows to still accommodate larger thoraces as well. The three columns were designed to allow for screws to be used to attach to the spine through the middle column while using wire ties where necessary that would go through the holes in the outer columns and around the vertebral column in order to provide additional support.

The strut supports coming from the back of the plate were designed to reduce flex in the fixture during impact. They originate at the top row of holes in the attachment array and extend down at oblique angles to the base.

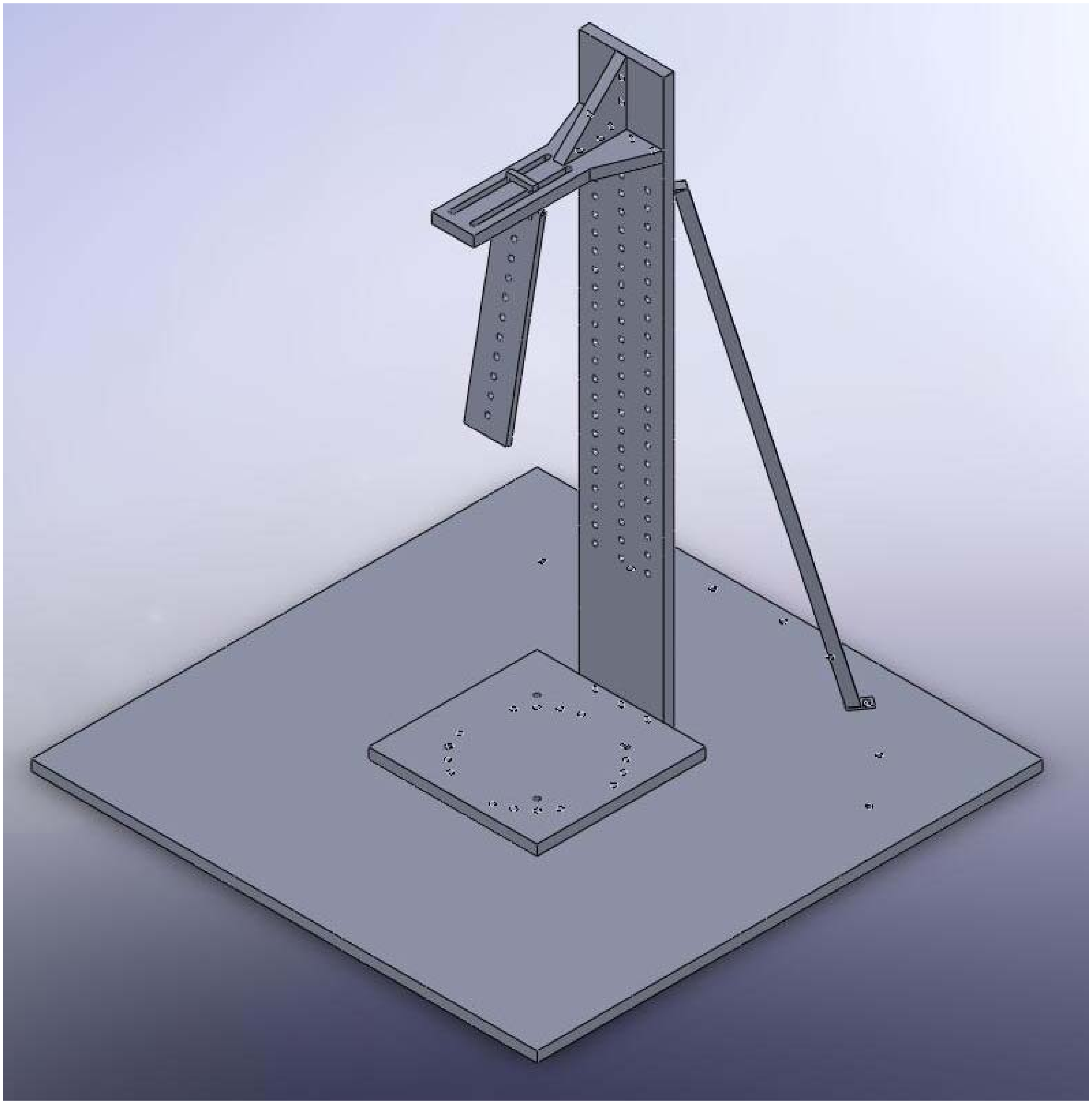


Figure 7: Initial Fixture Design

The horizontal piece attached to the top of the vertical plate is the sternum support. The sternum support was designed to allow the sternum to translate in the anterior-posterior direction during impact as shown in the results from Shaw et al. [4]. A close up of the hinge joint can be seen in Figure 8. There are two slots for the sternum attachment to slide along. The reason for using two slots instead of one is to reduce the rotation of the sternum about the vertical axis. The piece hanging down in the front is the sternum plate and is used to screw into the sternum. The sternum plate is made from ¼” T6061 aluminum instead of the usual 1/2” used for the rest of the fixture. This is because this is not a significant load bearing piece and the extra ½” of material is unnecessary. Figure 9 shows the actual fixture with a thorax attached and the sternum support being used.

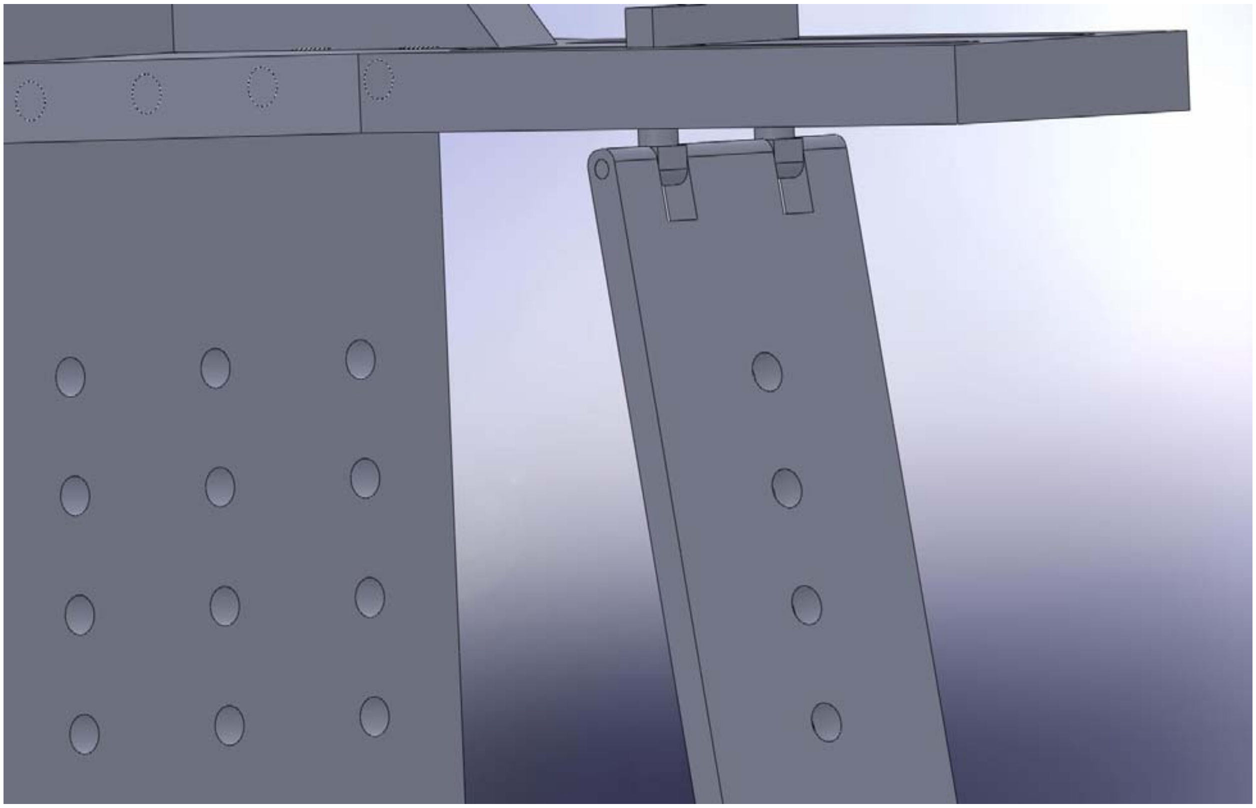


Figure 8: Close up of Sternum Support Hinge

Figure 9: Fixture w/ Thorax attached and sternum support

c. Design changes between first and second test

Between the first and second test there were some design changes that were necessary. The sternum support allowed for more rotation and displacement than was desired. This was due to the type of joint that was used to allow for the translation of the sternum. To correct the problem another linear guide support was added to the inferior side of the thorax and the sternum plate was extended to pass through this support as well. This allows the sternum plate to be secure at the top and the bottom and provides a much more stable solution to this design condition. Figure 10 shows the assembled fixture after the changes have been made. The width of the sternum plate was also reduced in order to be sure that the face of the impact ram would not impact the sternum plate during oblique impacts. A close up view of the lower support and new sternum plate is shown in Figure 11. The sternum plate is not attached at the bottom support, but is allowed to slide freely in the two slots. This joint was designed to still allow for the anterior-posterior translation, but to further restrict the rotation of the thorax.

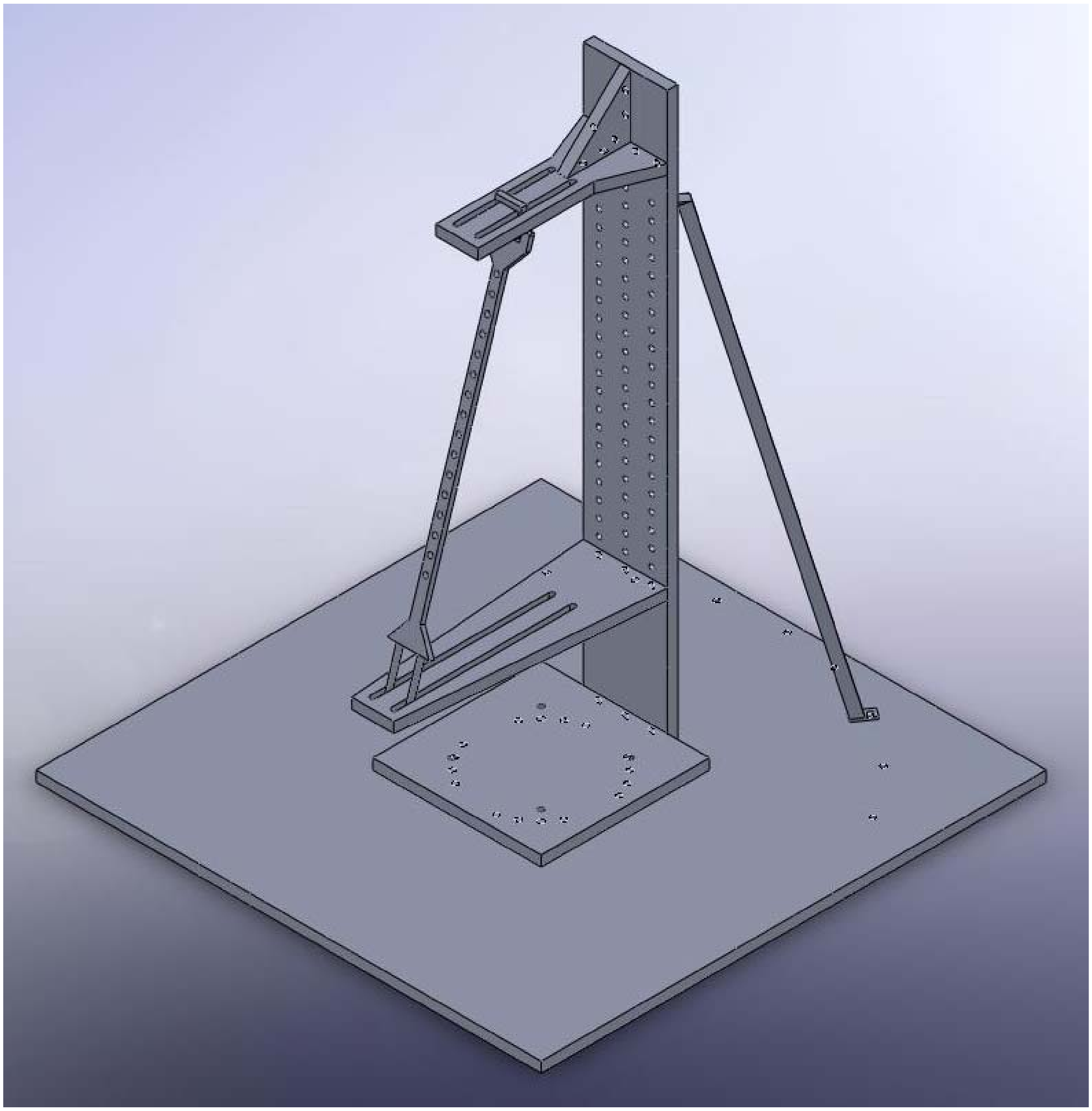


Figure 10: Assembled Fixture -- after design changes

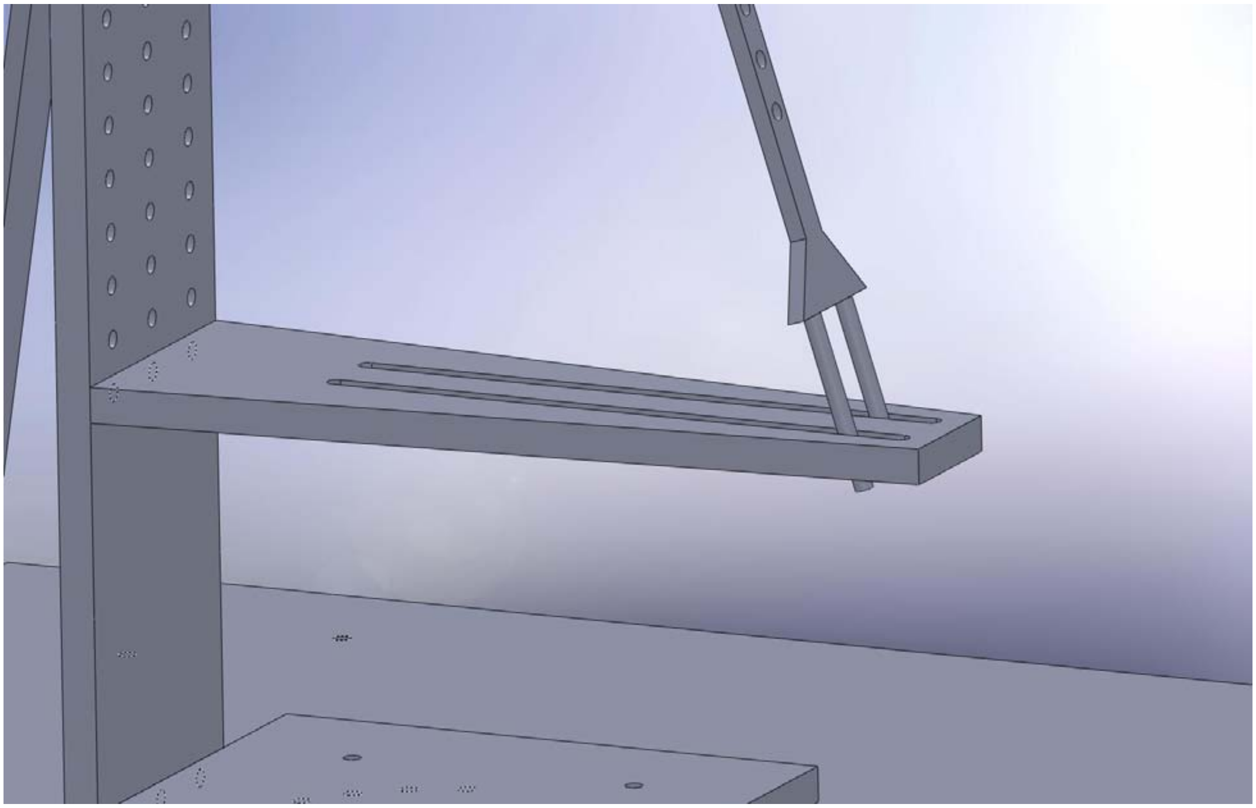


Figure 11: Close up view of lower sternum plate support

5. Methods

This chapter is divided into four sections. The first section will describe the procedure for dissection of the thorax. The second section will describe the attachment of the thorax to the fixture. The next section will discuss the types of instrumentation used. The fourth section will outline the testing process.

a. Dissection Procedure

This section will provide a step by step description of the dissection procedure used to remove the thoraces from the subjects. For an outline of the procedure, please see the appendix.

The dissection began with the subject in the prone position. The first step was to remove the skin on the back. This was done by making a midline incision from the external occipital protuberance to the level of the posterior superior iliac spines. Also, a transverse incision from the midline, superior to the scapula and to the tip of the acromion to a point on the arm halfway between the shoulder and elbow was made. Next, transverse incisions from the external occipital protuberance laterally to the base of the mastoid process, laterally from the midline along the posterior superior iliac spine, and laterally at the level of the inferior scapular angle were all made. Finally, the skin of the back was reflected away from the midline of the body. Figure 12 shows a subject with the skin reflected away from the back.

Figure 12: Dissection -- Skin removal from back

The next step was to remove the muscles that attach to the posterior aspect of the thoracic cage. This includes both the superficial muscles of the back as well as the deep layer of muscles. The superficial muscles include the trapezius muscle, rhomboid major and minor, and latissimus dorsi. The deep layer of muscles includes the erector spinae group. The erector spinae group is composed of the iliocostalis, longissimus, and spinalis muscles. Also, all muscles attachments to the posterior aspect of the scapula have been transected.

At this point a laminectomy was performed in order to remove the spinous processes of the vertebrae. The lamina of the vertebrae is the section that connects the transverse process of the vertebrae to the spinous process (Figure 13). Removal of the spinous process is necessary in order to ensure a flat surface for successful attachment to the fixture. To perform the laminectomy, a reciprocating saw was used to cut through each lamina and the spinous processes from each vertebrae were left connected and lifted from the spine after all the lamina had been transected. This procedure exposes the spinal cord and allows screws to be placed directly into the vertebral bodies.

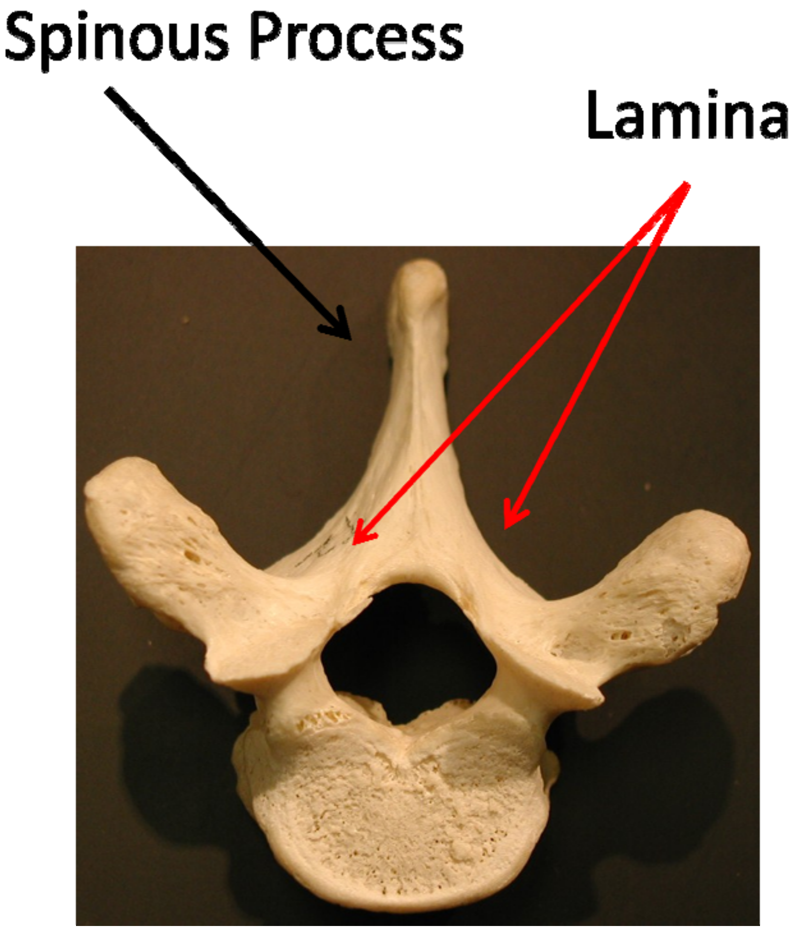


Figure 13: Lamina and Spinous Process

Next the subject must be flipped so that the subject is in the supine position. The first thing that was done, just as with the back, was to remove the skin. This was done by making a midline incision from the jugular notch to the xiphisternal junction, an incision along the clavicle, and an incision from the xiphoid process along the costal margin to the midaxillary line. The skin was then reflected away from the midline of the body.

Next, the muscle attachments to the anterior aspect of the thoracic cage were removed. This involved transecting the sternal head as well as the clavicular head of pectoralis major muscle and reflecting the muscle laterally. Pectoralis minor muscle was detached from ribs 3-5 making sure to leave the intercostals muscles attached. Also, serratus anterior muscle was removed from its attachment to the ribs and rectus abdominus muscle was removed from its attachment to the costal cartilage. Next, the clavicle was removed at the sternoclavicular joint. This allowed the entire arm and pectoral girdle to be removed.

To remove the head, the reciprocating saw was used once again to cut through the neck at a point above the first thoracic vertebrae. String was then used to tie off the aorta artery, the esophagus, and the common carotid arteries.

Next, the diaphragm muscle was carefully separated from the organs in the abdomen using both a scalpel and blunt dissection. Keeping the diaphragm intact was very important in order to be sure the contents of the thorax remained in their proper positions. After the diaphragm was separated from the abdomen, the reciprocating saw was used once more time to cut through the spine below the 12th thoracic vertebrae. Figure 14 shows the thorax just after removal with the diaphragm still intact

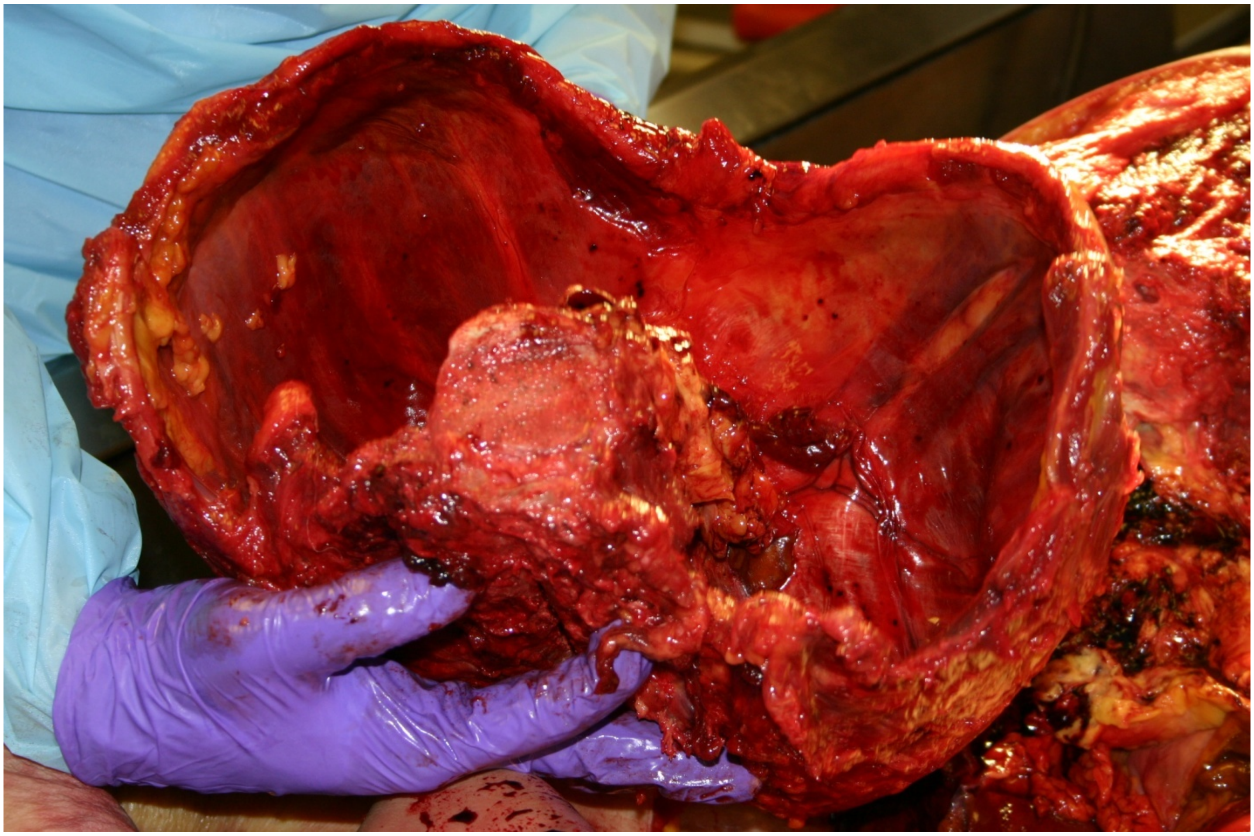


Figure 14: PMHS Thorax just after removal w/ intact diaphragm

b. Attachment Procedure

This section describes the methods used to attach the thorax to the test fixture. A step by step outline of this procedure can be found in the appendix.

The thorax was attached to the fixture using a number of screws that go through the vertical plate on the fixture and penetrate the vertebral bodies of the thorax. In order to attach the thorax, first the vertical plate of the fixture was laid flat and the thorax was placed on top of the plate in the prone position. To account for the curvature of the spine, three different size aluminum spacers

(1”, 0.5”, and 0.25”) were used as needed to provide a stable mounting surface for the thorax. Once the spacers were aligned, one screw was placed in the most inferior vertebrae by sliding the vertical plate over the edge of the table that was being used in order to allow acess to the back of the plate in order to place the first screw. This was repeated for the most superior vertebrae as well. Once there were screws in the superior and inferior aspects of the thorax the entire fixture was lifted into the vertical position and screws were placed into every vertebral body. Figure 15 shows the thorax attached to the fixture and provides a view of one of the spacers used to account for spinal curvature

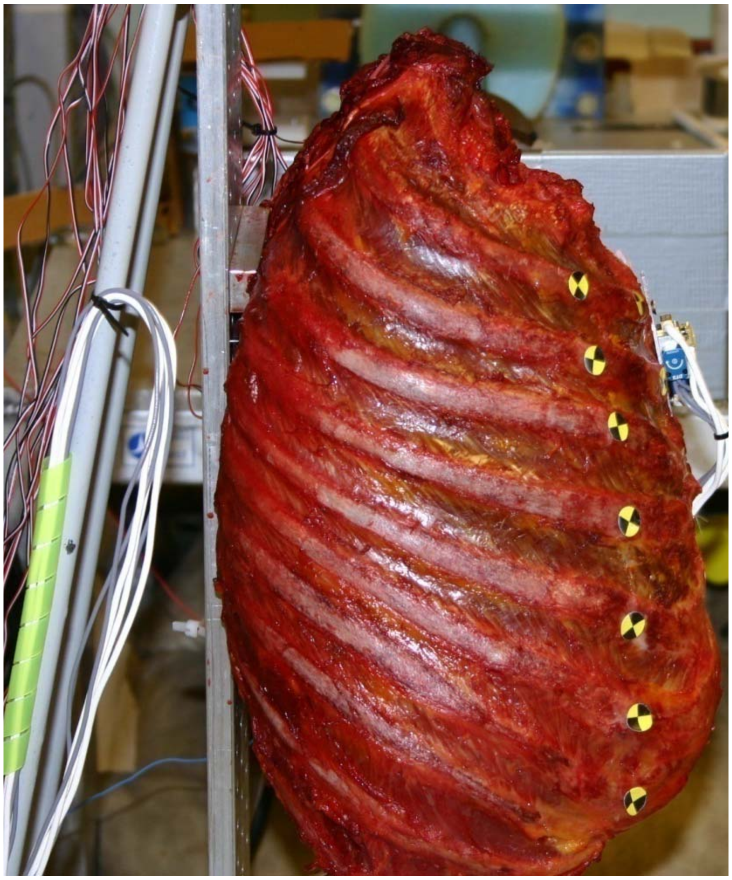


Figure 15: Thorax attached to fixture using spacers

c. Instrumentation

The instrumentation used for this experiment included strain gages, accelerometers, and rate gyrometers. Also, photo targets were placed to allow for motion capture data to be collected. This section outlines how these types of instrumentation were attached, and their implementation.

Each subject required the use of 9 strain gages. A strain gage was placed on ribs 2-10 on the left side of the thorax. The left side was the only side instrumented with strain gages, because that is the only side that was being impacted. These strain gages will mainly be used for fracture detection, but also provide qualitative support for impact response characteristics. These strain gages were attached using adhesive, with the sensitive axis of the gage aligned parallel with the rib. Figure 16 shows a sample of the strain gage setup. Each gage has remnants of a latex glove that was used to apply the adhesive to the strain gage and the ribs.

A 6 degree of freedom block was attached to the sternum. The block contained three accelerometers (one for each axis) and three rate gyrometers for recording angular velocity (again, one for each axis). This block was attached to the sternum using two small screws. Figure 17 shows the block attached to the sternum.

A series of photo targets were also used to track deflections using high speed video analysis. 5 columns of photo tagets were placed on the thorax and many stationary photo targets were placed on the fixture itself. These photo targets can be seen in both Figure 16 and Figure 17.

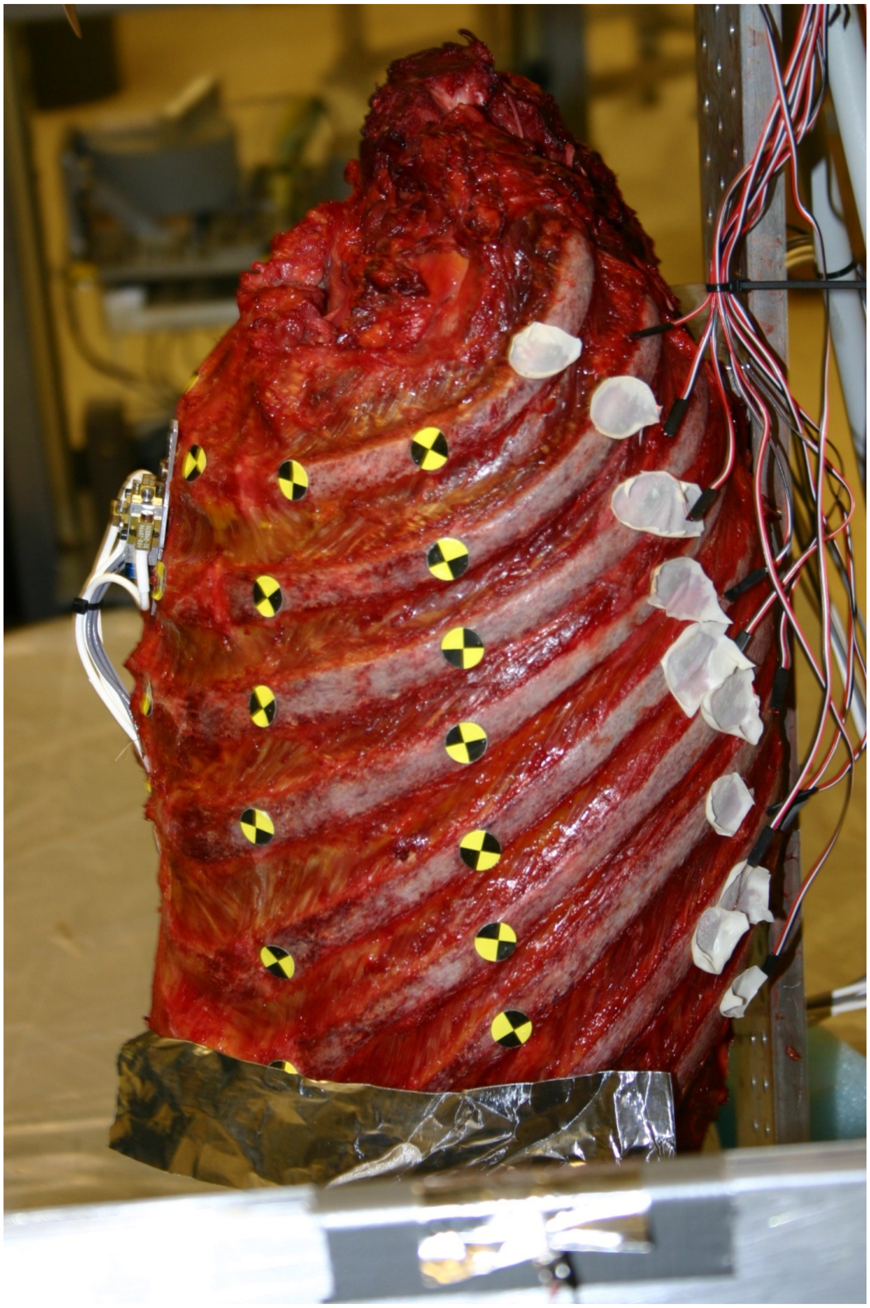


Figure 16: Strain Gage and Photo Target Placement

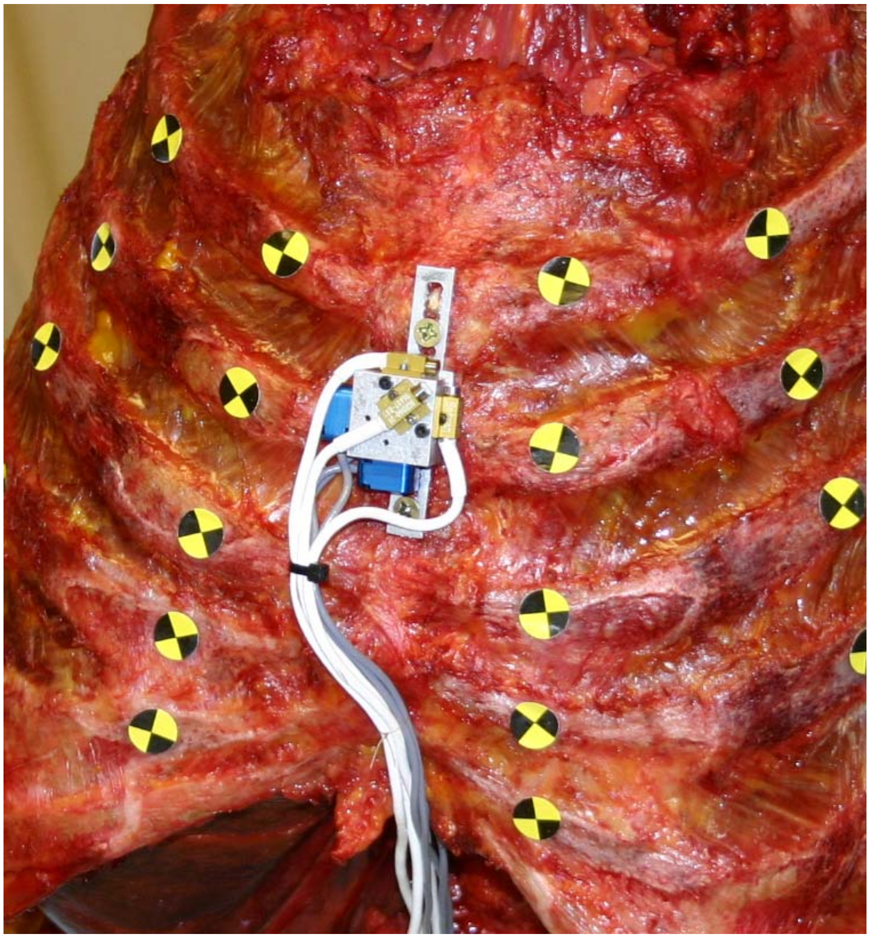


Figure 17: Sternum Accelerometer block

d. Testing Methods

i. Subject Information

There were two subjects used for testing during this study. A table of the relevant information of the subjects can be seen in Table 2. A more complete list of the anthropomorphic measurements for each subject can be found in the appendix.

Table 2: Subject Information

Subject	Gender	PMHS #	Test Ref #	Age [yrs]	Height [cm]	Weight [lbs]
1	Male	5760	0801	87	163	166
2	Male	5763	0802	79	192	192

ii. Test Information

Each subject was planned to undergo 4 impacts. One impact was to be in the lateral direction and one impact in the oblique direction for both cases of a restrained sternum and an unrestrained sternum. However, the first subject underwent 5 impacts due to the clamps that held the fixture to the table being loose for the third impact. Since the data from that test was tainted, the 3rd impact was repeated as the 4th impact on subject 1. Table 3 shows the test matrix for both subjects.

All of the oblique impacts were conducted at an angle of 30 degrees anterior to lateral in order to simulate the loading of a side impact automobile accident.

Table 3: Test Matrix

Subject	Test	Impact Direction	Impact Speed	Sternum Support	Impact Number
One	0801ODTH18LF01	Oblique	1.8 m/s	Free	1
	0801LDTH18LF02	Lateral	1.8 m/s	Free	2
	0801ODTH18LR03	Oblique	1.8 m/s	Restrained	3
	0801ODTH18LR04	Oblique	1.8 m/s	Restrained	4
	0801LDTH18LR05	Lateral	1.8 m/s	Restrained	5
Two	0802ODTH18LF01	Oblique	1.8 m/s	Free	1
	0802LDTH18LF02	Lateral	1.8 m/s	Free	2
	0802ODTH18LR03	Oblique	1.8 m/s	Restrained	3
	0802LDTH18LR04	Lateral	1.8 m/s	Restrained	4

iii. Data Collection

Data was collected using a 96-channel Yokogawa Electric Corporation WE7000 data acquisition system. Analog to digital conversion was performed at a sampling rate of 20,000 Hz. The bias was removed and the data filtered according to SAE J211 standards, where sternum accelerations are filtered at Channel Filter Class (CFC) 1000, and sternum angular velocities at CFC 60.

6. Results

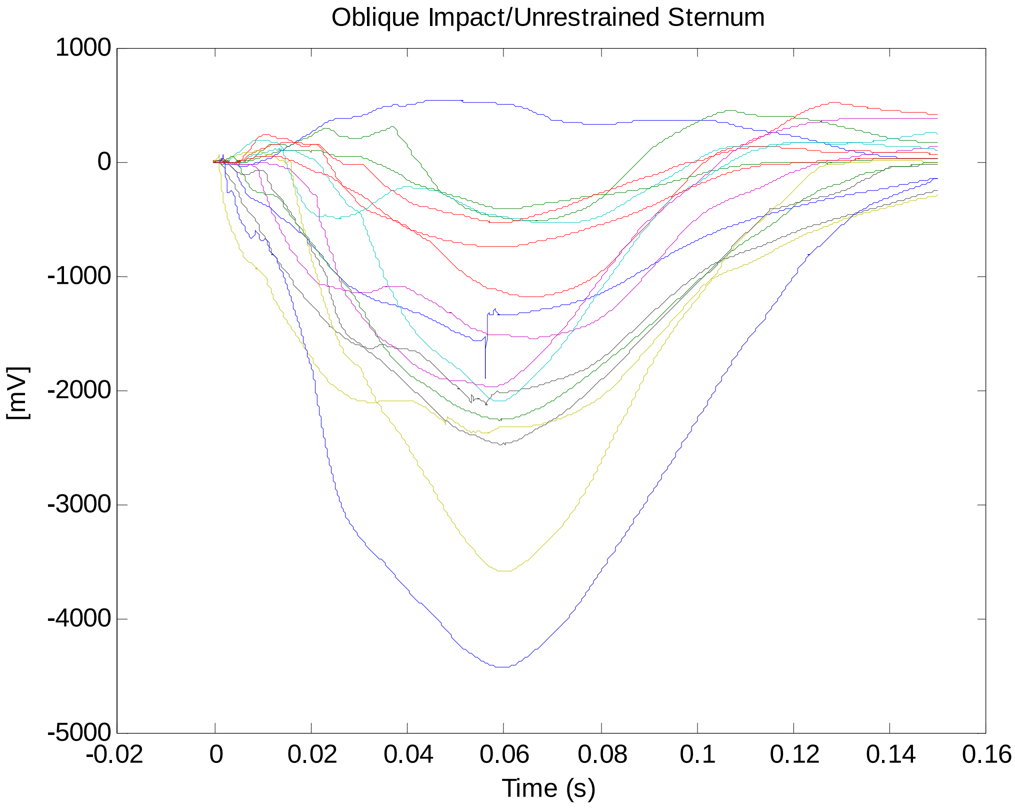


Figure 18: Strain gage data from 1st impact

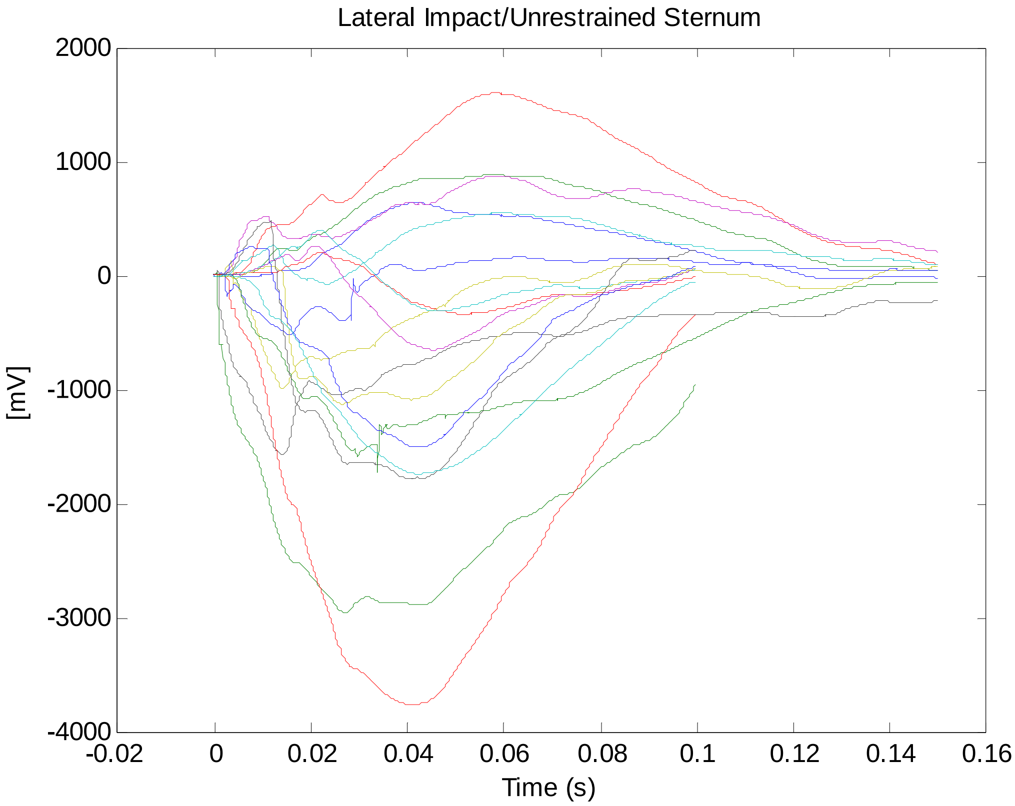


Figure 19: Strain gage data from 2nd impacts

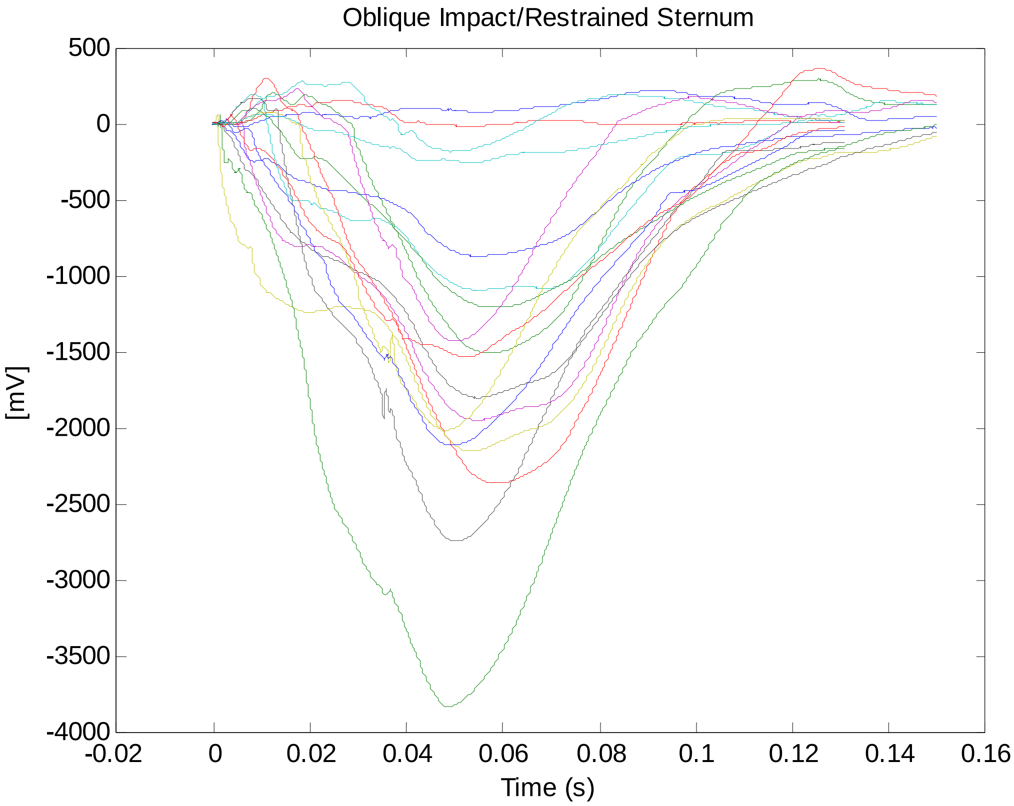


Figure 20: Strain gage data from 3rd impacts

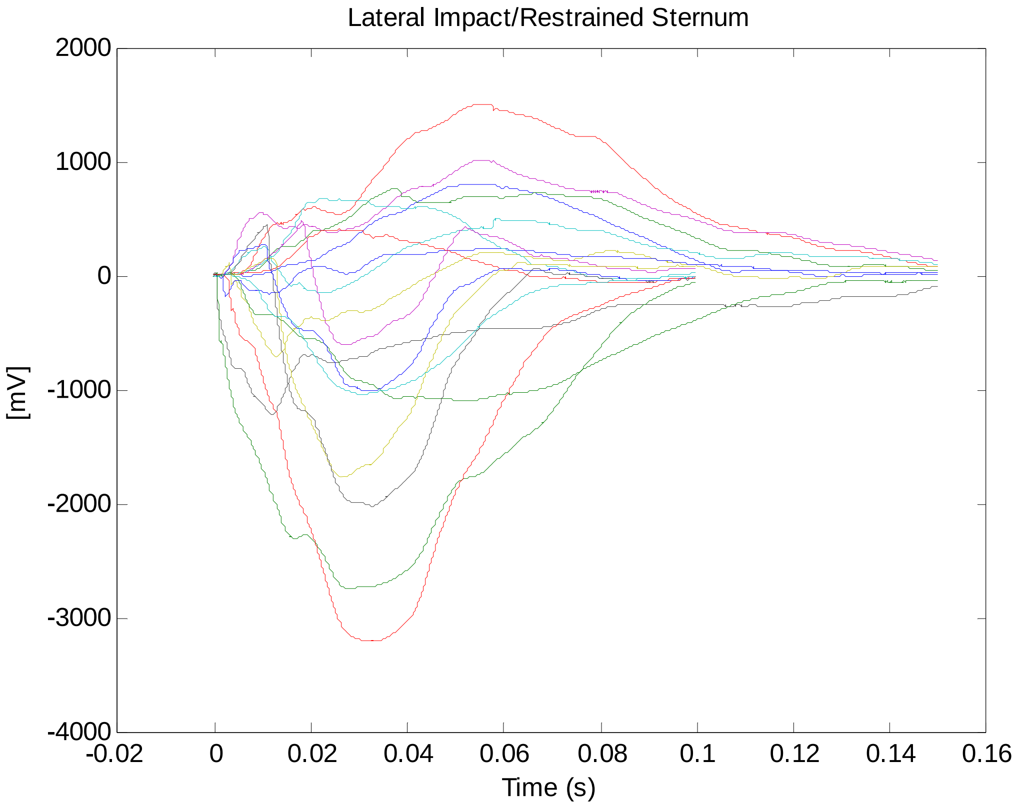


Figure 21: Strain gage data from 4th impacts

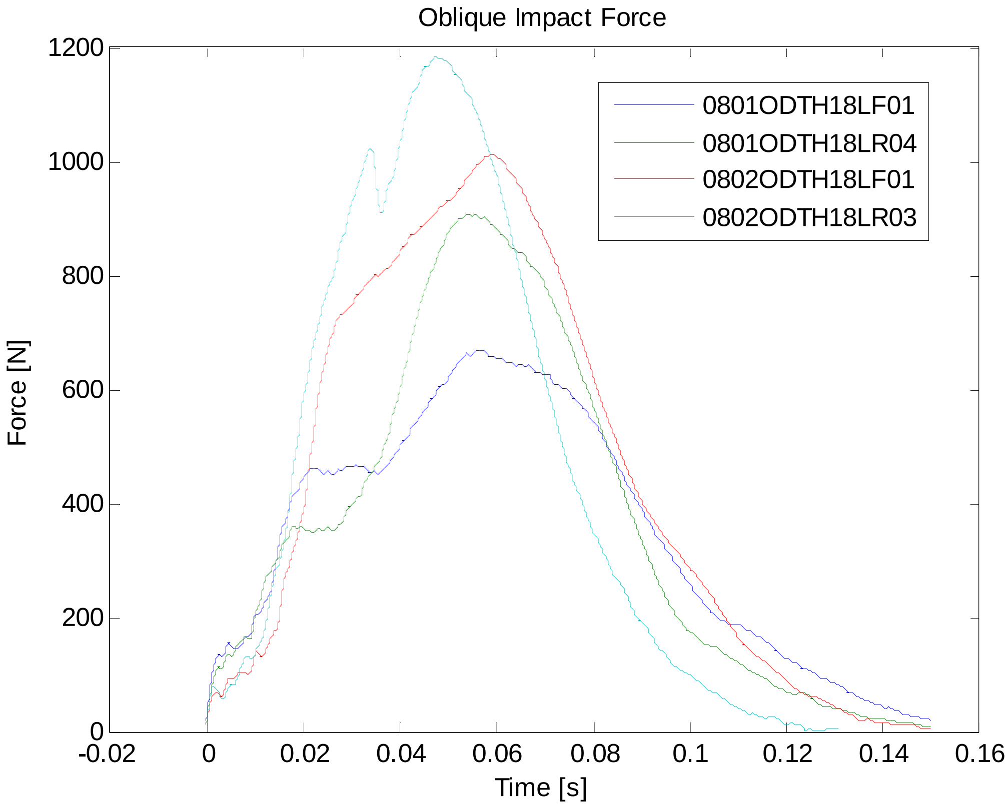


Figure 22: Ram impact force for oblique impacts

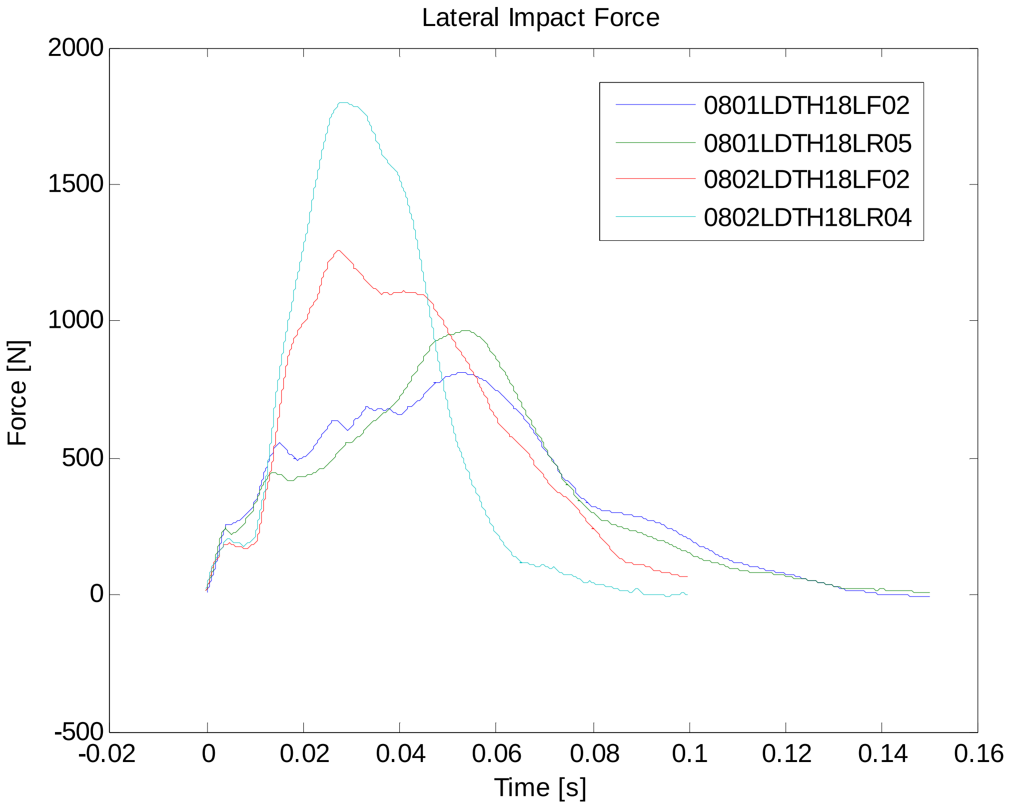


Figure 23: Ram impact force for lateral impacts

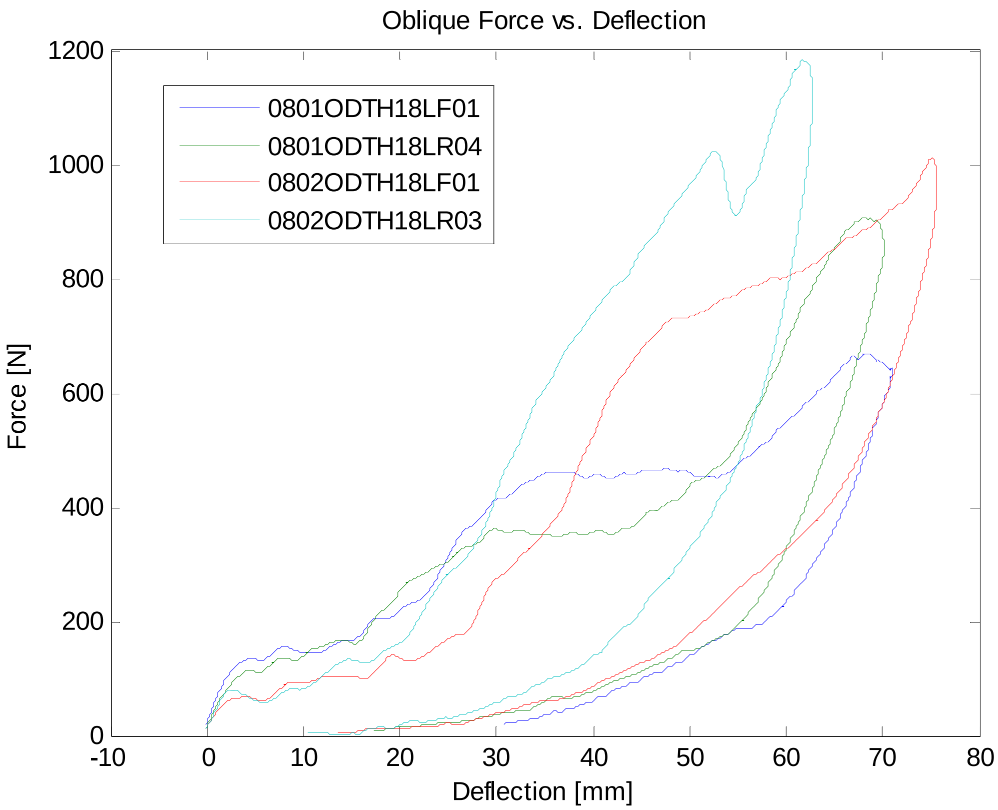


Figure 24: Force Deflection Curves for Oblique Impacts

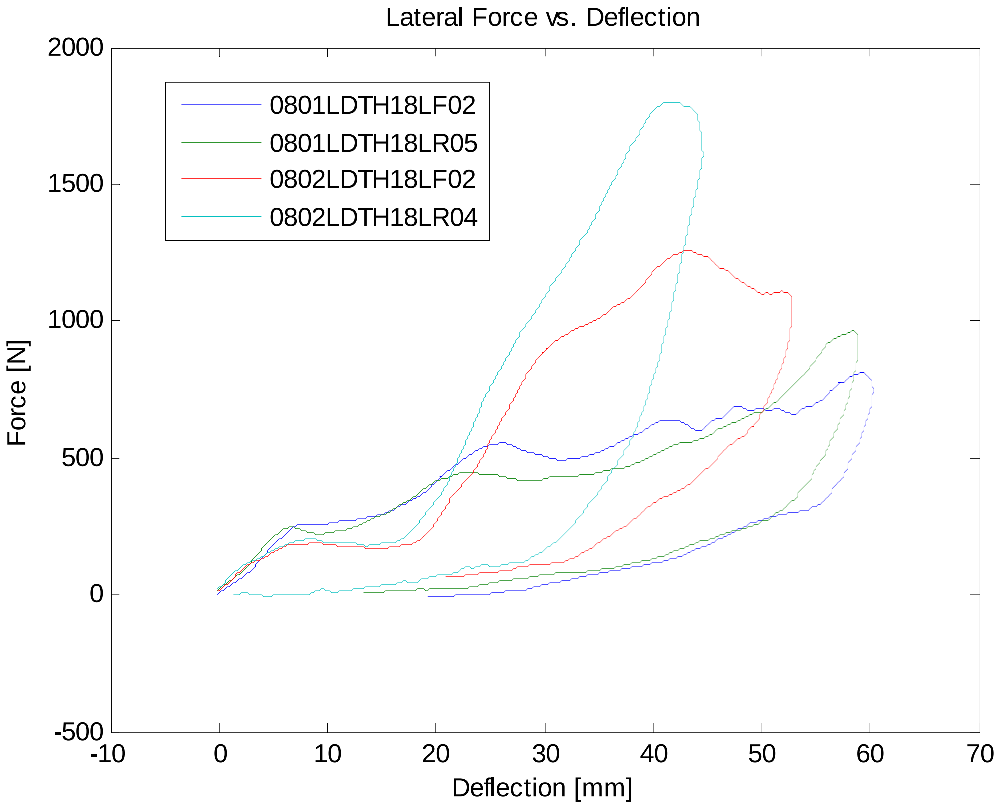


Figure 25: Force Deflection Curve for Lateral Impact

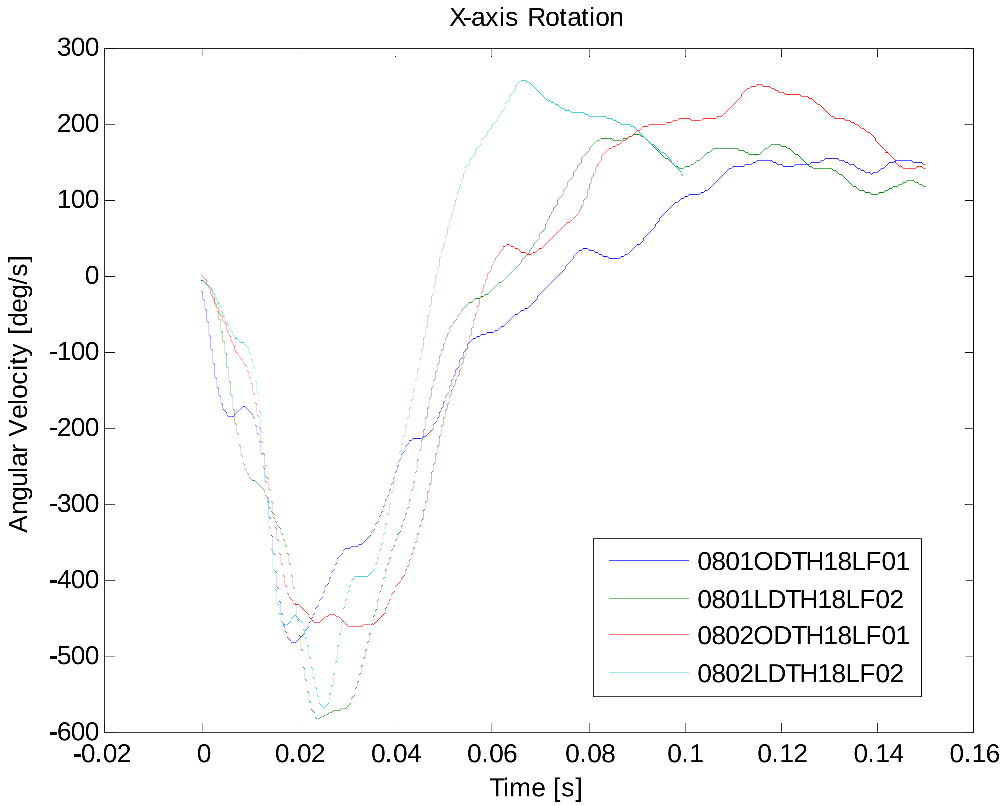


Figure 26: X-axis rotation for unrestrained sternum tests

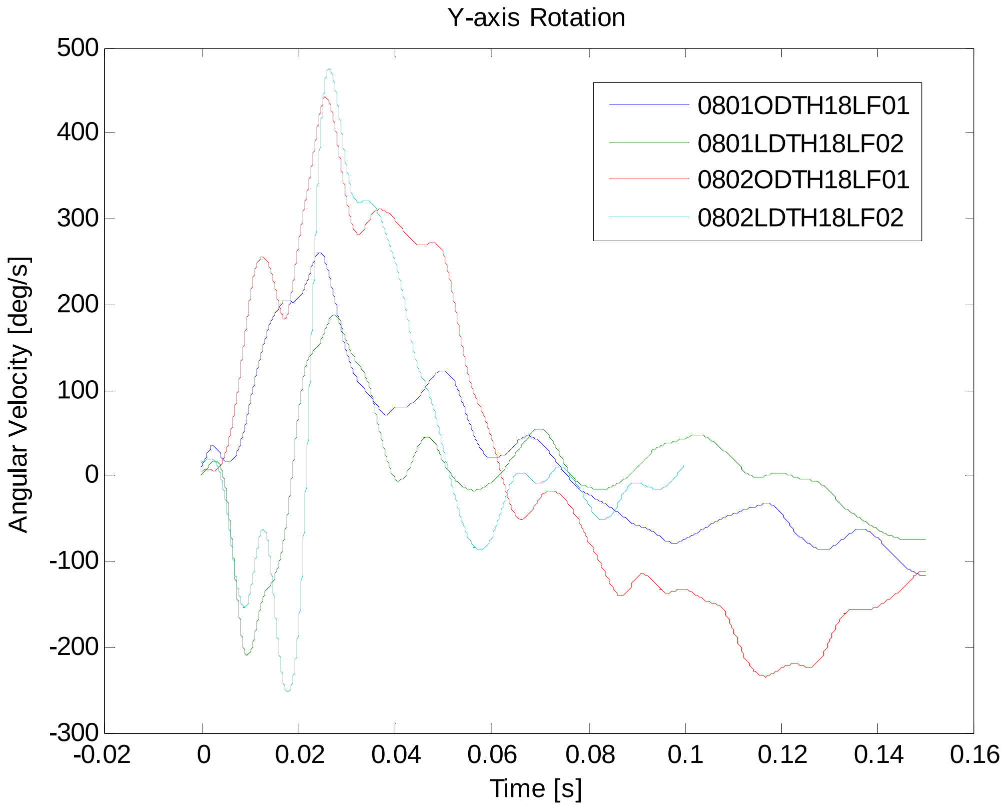


Figure 27: Y axis rotation for unrestrained sternum tests

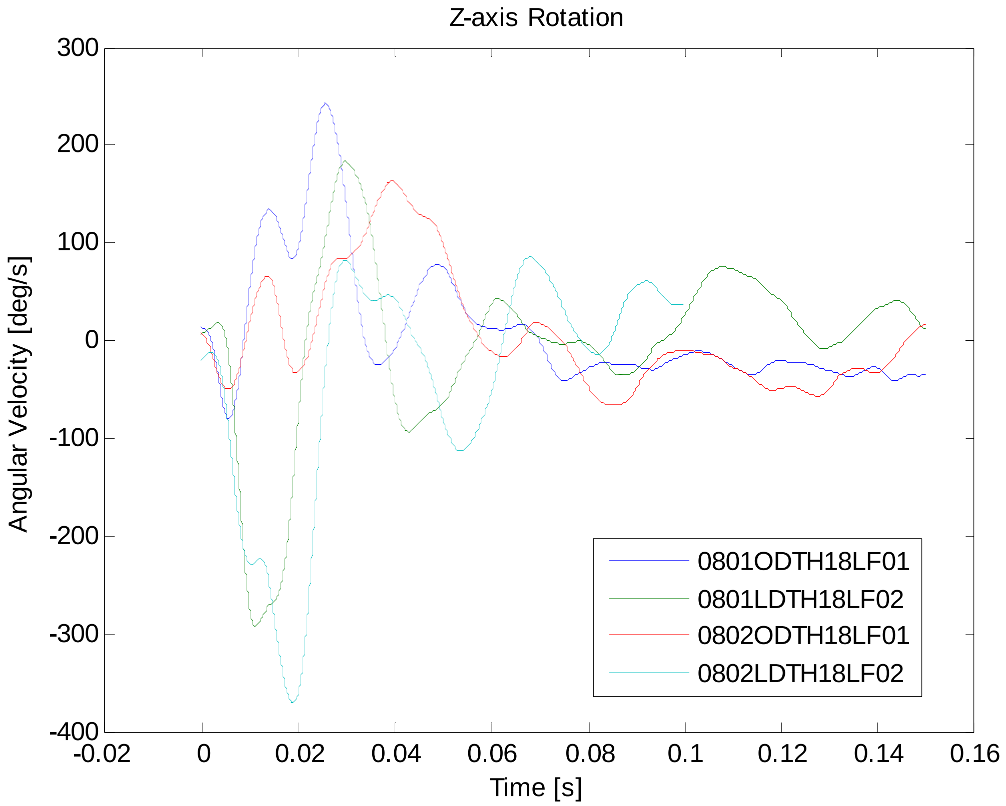


Figure 28: Z-axis rotation for unrestrained tests

7. Discussion

The results for the impacts of the two subjects are shown in Figures 18-28. The strain gage data is shown in Figures 18-21. The results from the strain gages is mainly used to determine fracture in the ribs. If a fracture has occurred it will be shown as a sudden jump in the strain of a rib. Two fractures occurred during the oblique, restrained sternum test on the second subject. Pictures of the fractures can be found in the appendix. It is important to note the shape of the strain gage curves. During the four oblique tests, the shapes are comparable. This is also the case for the four lateral impacts. This shows that the impacts were affecting the thorax consistently throughout the different tests.

The force deflection curves (Figures 24-25) agree with the findings of Shaw et al. [4]. For the oblique response, it takes less force to deflect the thorax the same amount as the lateral response. Also, the strain gage data can be used qualitatively to characterize the response as well. For the oblique impacts, most of the ribs are in compression, but for the lateral impacts many of the ribs are put in tension. This implies that during an oblique impact, the response is more localized deflection than rigid body motion of the entire thorax. The opposite is true for later impacts. The strain gages show most of the ribs in tension which would imply that the thorax is behaving more like a rigid body and rotating as a whole.

There are anatomical explanations for this rotation as well as the characteristics of the different impact directions. The reason that the oblique impact is causing more localized deflection than the lateral impact is because of te difference in the type of joint at the ends of the ribs. The joints between the vertebrae and the ribs are very bony, fibrous, and stiff. The joints between the sternum and the ribs (sternocostal joints) are actually synovial joints. Synovial joints provide much more articulation than fibrous joints and would allow for much more deflection in their proximity. The stiff, fibrous joints prevent the ribs from deflecting locally near the joint and force the ribs to transmit the force leading to more rigid body motion.

Most of the rotation was expected to occur around the spinal column (z-axis). This was not the case as shown in Figures 26-28. These figures only include the unrestrained sternum tests where the sternum accelerometer block was used. When viewing the results of the rotation of the sternum during the unrestrained impacts it becomes very clear that there is a large rotation about the x-axis, which is the axis oriented in the anterior-posterior direction. This result is unexpected and only becomes noticeable after removing the thorax from the subject. It is unknown whether or not this rotation is as prevalent in full body impacts due to the muscle attachments that connect the inferior aspect of the thorax to the superior aspect of the pelvis.

a. Conclusions

- Force vs. Deflection results agree with Shaw et al. [4].
- Rotation of thorax was about a different axis than expected
- Lateral stiffness is greater in magnitude than Oblique stiffness

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Appendix

a. Dissection Procedure

1. Lay subject in prone position.
2. Remove skin
    a. Make a midline incision from the external occipital protuberance to the level of the posterior superior iliac spines
    b. Make transverse incisions in the following areas:
        i. From the midline, superior to the scapular and to the tip of the acromion, to a point on the arm halfway between the shoulder and elbow
        ii. From the external occipital protuberance laterally to the base of the mastoid process
        iii. Laterally from the midline along the posterior superior iliac spine
        iv. Laterally at the level of the inferior scapular angle
        v. Reflect the skin of the back away from the midline of the body
3. Remove muscles from posterior attachments to cage
    a. Remove muscles from back:
        i. Superficial muscles
            1. Trapezius muscle, rhomboid major and rhomboid minor, latissimus Dorsi, etc.
        ii. Deep layer of muscles
            1. Iliocostalis, Longissimus, Spinalis

    b. Ensure all muscular attachments from the back to the scapula have been transected.

4. Lay Subject supine
5. Remove Skin
    a. Make midline incision from jugular notch to xiphisternal junction
    b. Make a skin incision from jugular notch along the clavicle to the acromion continuing to a point approximately halfway down the arm.
    c. Make incision from xiphoid process along the costal margin to the madaxillary line
    d. Reflect skin away from midline of body
6. Remove muscle attachments to thoracic cage
    a. Relax the sterna head of pectoralis major by flexing and adducting the arm
    b. Insert fingers posterior to the inferior border of the pectoralis major.
    c. Create space between muscle and clavipectoral fascia by pushing fingers superiorly
    d. Use scissors to detach the pectoralis major from the sternum and clavicle
    e. Reflect laterally
    f. Use scissors to detach pectoralis minor from ribs 3-5. Reflect superiorly leaving the muscle attached to the coracoid process. Leave intercostals muscles attached.
    g. Detach the serratus anterior muscle from its proximal attachments on ribs 1-8 and reflect it laterally.

    h. Remove the rectus abdominus from its attachment to the costal cartilage of ribs 5 to 7.

7. Remove clavicle from thoracic cage at sternoclavicular joint
8. From inferior aspect of thoracic cage remove diaphragm from ribs
9. Open neck and cut through neck muscles
    a. Make a skin transverse cut of skin above sterna notch
    b. Make a midline incision 3-4” superior
    c. Reflect skin superior lateral on both sides.
    d. Cut through all muscles in the anterior portion of the neck
    e. Cut trachea and esophagus
    f. Cut jugular vein and carotid artery & brachial plexus of nerves
    g. Cut above disc between C7 and T1 vertebrae
10. Non-removal of viscera technique
    a. Clean off inferior edge of ribs 10, 11, 12 to define the edge of the cage
    b. Pull abdominal viscera inferiorly
    c. Cut through IVC, esophagus & descending aorta as they emerge through diaphragm
    d. Cut disc between T12 and L1 vertebrae
    e. Lift thoracic cage anterior to remove
11. Removal of viscera technique
    a. Clean off inferior edge of ribs 10, 11, 12 to define the edge of the cage
    b. Pull abdominal viscera inferiorly

c. Remove diaphragm from inferior margins of ribs

d. Place arm up through inferior outlet of thoracic cage

e. Grab trachea, esophagus, etc. and pull inferiorly

f. As you pull inferiorly, remove adhesions between thoracic cage and lungs

    i. Lungs, heart, etc will pull up and off of vertebral column.

    ii. Pull “block” out of cage inferiorly

g. Cut disc between T12 and L1 vertebrae

h. Lift thoracic cage anterior to remove.

b. Attachment Procedure

1. Lay thoracic cage in prone position
2. Removal of Spinous Process
    a. Use straightedge to create mark on spinous processes in line with transverse costal facet in order to create a flat surface posteriorly
    b. Use Dremel to remove spinous processes at marked locations for T1 through T12.
3. Remove sternum attachment from fixture and remove vertical portion from base
4. Attach thoracic cage to fixture
    a. Place vertical portion of fixture on thoracic cage starting at the top of the fixture
    b. Align as many center holes as possible with posterior portion of vertebrae
    c. Use wire through outer holes and around spine to attach to fixture
    d. Place spacers as needed to account for curvature of spine
        i. Place a 1” spacer at the level of T1
            1. Use additional spacers as needed for T2, T3, etc.
        ii. Place a 0.5”spacer at the level of T12
            1. Use additional spacers as needed for T11, T10, etc.
    e. After desired positioning is achieved, screw into spine through center hole to secure for testing.
5. Place thoracic cage with portion of fixture back on the base of fixture and secure at desired impact angle
6. Reattach sternum attachment to vertical portion of fixture
    a. Attach to sternum using screws through the hinge on the end of the fixture.

c. Test day Checklist

Notification Phase:

____ Contact Team Members (Josh, Rod, Joe, John)

____ Determine Preparation and Test Schedule

____ Thaw subjects from freezer 3 days in advance

____ Prepare lab for thoracic testing

____ Set-up data acquisition system including completing instrumentation check

____ Ensure all needed equipment from VRTC is brought to IBRL

Dissection Phase:

____ Take necessary Anthropomorphic Measurements on whole body

____ Follow Dissection protocol to remove thoracic cage

____ Weigh the denuted thorax

Instrumentation & Fixture Mounting:

____ Attach Spinal Accelerometer mount and instrumentation (Thimble-screw)

____ Record instrumentation serial numbers

____ Attach Sternum Accelerometer mount and instrumentation (Screw)

____ Record instrumentation serial numbers

____ Follow attachment protocol to attach the deunted thorax to the test fixture

Positioning Phase:

____ Ensure that universal precautions are being enforced

____ Position thoracic fixture in front of impactor

____ Take measurements for chest contour and mark measurement locations on plastic strip with paint markers

____ Transfer measurements onto board and recreate chest contour

____ Place subject in impact position and push ram back to initial position

____ FARO positioning measurements of accelerometer mounting blocks

<u>Test Performance Phase:</u>

____ Ensure that universal precautions are being enforced

____ Make sign board

____ Verify the configuration data acquisition system

____ Clean impactor ram and lubricate the shaft

____ Check connection of ram accelerometer, linear pot, and light traps

____ Set-up high speed camera and lighting

____ Check positioning to ensure **FREE FLIGHT** of the ram

____ Use high speed cameras to check for proper alignment of the cadaver

____ Record the distance from the cameras to the cadaver

____ Connect all instrumentation, verify continuity, balance, etc.

____ Zero all recording channels (ecept chestband)

____ Place photographic-targets on the cadaver

____ Place inch tape stick on ram frame for photographic analysis

____ Place sign board

____ Place on event tape and hook up event switches

____ Final camera focus

____ Still photography

____ Ensure all test data sheets are complete

____ Event power supply turned on

____ Cameras triggered and lights turned on

____ Ram fire turned on and ready

____ Conduct 1st Test

Post-Test 1 Phase and Repositioning:

____ Ensure that universal precautions are being enforced

____ Record velocities from light traps, pressure, date, time, etc.

____ Still photography

____ Download the data from the high-speed cameras

____ Rotate the fixture 30 degrees

____ Place subject in impact position and push ram back to initial position

____ Record positioning measurements of accelerometer mounting blocks

____ Use high speed cameras to check for proper alignment of the cadaver

____ Update the sign board

____ Check connection of ram accelerometer, linear pot, and light traps

____ Check positioning to ensure **FREE FLIGHT** of the ram

____ Record the distance from the cameras to the cadaver

____ Connect all instrumentation, verify continuity, balance, etc.

____ Zero all recording channels (ecept chestband channels)

____ Place sign board

____ Place on event tape and hook up event switches

____ Still photography

____ Ensure all test data sheets are complete

____ Event power supply turned on

____ Cameras triggered and lights turned on

____ Ram fire turned on and ready

____ Conduct 2nd Test

Post-Test 2 Phase:

____ Ensure that universal precautions are being enforced

____ Record velocities from light traps, pressure, date, time, etc.

____ Still photography

____ Download the data from the high-speed cameras

____ Remove the cadaver and place on gurney

____ Remove all instrumentation

____ Record/note any relevant observations ** **ESPECIALLY INSTRUMENTATION CHANGES & Injuries**

Laboratory Clean-up:

____ Ensure that universal precautions are being enforced

____ Complete all steps on the workroom decontamination checklist

____ Place all contaminated disposables in bio-hazard container

____ Soak and/or scrub all non-sharp instruments with bleach solution

____ Scrub counter tops, table tops, impactor surface, and gurney with bleach solution

____ Check instrumentation and cables for any blood contamination, and if found, remove with bleach solution

____ Sweep and mop floor with bleach solution

____ Complete all steps on the hand washing station inspection checklist

____ Check stock of protective clothing and, if necessary, restock for net test

____ Sign and date the workroom decontamination checklist

d. Data Processing Script

```
'--------------------------------------------------------------------------------------------------
'Removing the Bias (look at raw data to determine the duration)
'--------------------------------------------------------------------------------------------------
dim i, k, mean
dim StartTime, StopTime, StartPoint, StopPoint, action

StartTime = -0.00010 'Put in Start Time
StopTime = -0.00005  'Put in Stop Time
StartPoint = PNo("[1]/Time",StartTime)
StopPoint = PNo("[1]/Time",StopTime)
Call ChnGet(0, 1, "Select Channels for Offset Removal")
For i=1 To ChnSelCount(ChnNoStr1)
  k=ChnSelGet(ChnNoStr1,i)
  STATSEL(1)      ="No"
  STATSEL(2)      ="No"
  STATSEL(3)      ="No"
  STATSEL(4)      ="No"
  STATSEL(5)      ="No"
  STATSEL(6)      ="Yes"
  STATSEL(7)      ="No"
  STATSEL(8)      ="No"
  STATSEL(9)      ="No"
```

```
STATSEL(10)     ="No"
STATSEL(11)     ="No"
STATSEL(12)     ="No"
STATSEL(13)     ="No"
STATSEL(14)     ="No"
STATSEL(15)     ="No"
STATSEL(16)     ="No"
STATSEL(17)     ="No"
STATSEL(18)     ="No"
STATSEL(19)     ="No"
STATSEL(20)     ="No"
STATSEL(21)     ="No"
STATSEL(22)     ="No"
STATCLIPCOPY     =0
STATCLIPVALUE    =0
STATFORMAT       =""
STATRESCHN       =0
Call ChnPropSet(k, "description")
Call STATBLOCKCALC("Channel",StartPoint & "-" & StopPoint,k)
Mean=statarithmean
unit = ChnDim(k)
action = ChnPropGet(k, "description")
call FormulaCalc("Ch(" & k & "):=Ch(" & k & ")-" & mean)
```

```
  Call ChnPropSet(k, "description", action & "zeroed from " & StartTime & " - " & StopTime
&", ")

  ChnDim(k) = unit

Next


'-----------------------------------------------------------------------------------------------

' Data processing (filtering (CFC), define impact force, etc )

' BWF vs. CFC (100->60, 300->180, 1000->600, 1650->1000)

'-----------------------------------------------------------------------------------------------

' Pneumatic Impactor (a linear pot, an accelerometer, a 6-axis loadcell)

' Acceleration, Displacement, Force&Moment(LC)

' Inertial Force(mass of impactor, half of loadcell, 4-screws etc)

' Chin: 2.586465 kg, Tibia: 22.75 kg

'-----------------------------------------------------------------------------------------------

' Ram Accelerometer

'-----------------------------------------------------------------------------------------------

Call
CHNCFCFILTCALC("[1]/Time","[1]/RAMXG","[1]/RAMXGp","CFC_180",0,"EndPoints",10)

ChnDim("[1]/RAMXGp") = "g"


' Velocity from Ram accelerometer

Call FormulaCalc("ch('[1]/RAMXGpM'):= ch('[1]/RAMXGp')*9.80665")' g -> M/sec^2

Call CHNINTEGRATE("[1]/Time","[1]/RAMXGpM","[1]/RAMXGp_Vel")

ChnDim("[1]/RAMXGp_Vel") = "m/Sec"

Call CHNDELETE("[1]/RAMXGpM")
```

```
' Displacement from Ram accelerometer (double integrated)

Call CHNINTEGRATE("[1]/Time","[1]/RAMXGp_Vel","[1]/RAMXGp_Dis")
Call FormulaCalc("ch('[1]/RAMXGp_Dis'):= ch('[1]/RAMXGp_Dis')*1000")
ChnDim("[1]/RAMXGp_Dis") = "mm"

' Inertial force of the impactor including half of loadcell and 4-screws
Call FormulaCalc("ch('[1]/InertialFz'):= ch('[1]/RAMXGp')*9.80665*1.70979")
ChnDim("[1]/InertialFz") = "N"

'-----------------------------------------------------------------------------------------------
' Ram Displacement from linear pot
'-----------------------------------------------------------------------------------------------
Call
CHNCFCFILTCALC("[1]/Time","[1]/RAMXD","[1]/RAMXDp","CFC_180",0,"EndPoints",10)
ChnDim("[1]/RAMXDp") = "Cm"

'-----------------------------------------------------------------------------------------------
' Ram 6-axis Load Cell
'-----------------------------------------------------------------------------------------------
Call
CHNCFCFILTCALC("[1]/Time","[1]/RAMFX","[1]/RAMFXp","CFC_180",0,"EndPoints",10)
ChnDim("[1]/RAMFXp") = "N"
```

```
Call
CHNCFCFILTCALC("[1]/Time","[1]/RAMFY","[1]/RAMFYp","CFC_180",0,"EndPoints",10)

ChnDim("[1]/RAMFYp") = "N"

Call
CHNCFCFILTCALC("[1]/Time","[1]/RAMFZ","[1]/RAMFZp","CFC_180",0,"EndPoints",10)

ChnDim("[1]/RAMFZp") = "N"

Call
CHNCFCFILTCALC("[1]/Time","[1]/RAMMX","[1]/RAMMXp","CFC_180",0,"EndPoints",10
)

ChnDim("[1]/RAMMXp") = "N"

Call
CHNCFCFILTCALC("[1]/Time","[1]/RAMMY","[1]/RAMMYp","CFC_180",0,"EndPoints",10
)

ChnDim("[1]/RAMMYp") = "N"

Call
CHNCFCFILTCALC("[1]/Time","[1]/RAMMZ","[1]/RAMMZp","CFC_180",0,"EndPoints",10
)

ChnDim("[1]/RAMMZp") = "N"


'----------------------------------------------------------------------------------------------------

' Impact force including inertial compensation and displacement from linear pot

'----------------------------------------------------------------------------------------------------


Call FormulaCalc("ch('[1]/CompForce'):= (ch('[1]/RAMFZp')-ch('[1]/InertialFz'))*-1") '-1: make
a positive curve

ChnDim("[1]/CompForce") = "N"

Call FormulaCalc("ch('[1]/RamDisp'):= ch('[1]/RAMXDp')*-10")' -10: change cm to mm and
make a positive curve
```

```
ChnDim("[1]/RamDisp") = "mm"



' Sternum
'X
Call CHNCFCFILTCALC("[1]/Time","[1]/SPNEXG","[1]/SPNEXGp","CFC_1000",0,"EndPoints",10)
ChnDim("[1]/SPNEXGp") = "g"

' Velocity
Call FormulaCalc("ch('[1]/SPNEXGpM'):= ch('[1]/SPNEXGp')*9.80665")' g -> M/sec^2
Call CHNINTEGRATE("[1]/Time","[1]/SPNEXGpM","[1]/SPNEXGp_Vel")
ChnDim("[1]/SPNEXGp_Vel") = "m/Sec"
Call CHNDELETE("[1]/SPNEXGpM")
Call CHNINTEGRATE("[1]/Time","[1]/SPNEXGp_Vel","[1]/SPNEXGp_Dis")
ChnDim("[1]/SPNEXGp_Dis") = "m"

' Y
Call CHNCFCFILTCALC("[1]/Time","[1]/SPNEYG","[1]/SPNEYGp","CFC_1000",0,"EndPoints",10)
ChnDim("[1]/SPNEYGp") = "g"
```

```
' Velocity

Call FormulaCalc("ch('[1]/SPNEYGpM'):= ch('[1]/SPNEYGp')*9.80665")' g -> M/sec^2

Call CHNINTEGRATE("[1]/Time","[1]/SPNEYGpM","[1]/SPNEYGp_Vel")

ChnDim("[1]/SPNEYGp_Vel") = "m/Sec"

Call CHNDELETE("[1]/SPNEYGpM")

Call CHNINTEGRATE("[1]/Time","[1]/SPNEYGp_Vel","[1]/SPNEYGp_Dis")

ChnDim("[1]/SPNEYGp_Dis") = "m"

' Z

Call
CHNCFCFILTCALC("[1]/Time","[1]/SPNEZG","[1]/SPNEZGp","CFC_1000",0,"EndPoints",1
0)

ChnDim("[1]/SPNEZGp") = "g"


' Velocity

Call FormulaCalc("ch('[1]/SPNEZGpM'):= ch('[1]/SPNEZGp')*9.80665")' g -> M/sec^2

Call CHNINTEGRATE("[1]/Time","[1]/SPNEZGpM","[1]/SPNEZGp_Vel")

ChnDim("[1]/SPNEZGp_Vel") = "m/Sec"

Call CHNDELETE("[1]/SPNEZGpM")

Call CHNINTEGRATE("[1]/Time","[1]/SPNEZGp_Vel","[1]/SPNEZGp_Dis")

ChnDim("[1]/SPNEZGp_Dis") = "m"


' DTS

' X
```

```
Call
CHNCFCFILTCALC("[1]/Time","[1]/SPNEXdeg","[1]/SPNEXdegp","CFC_60",0,"EndPoints",
10)

ChnDim("[1]/SPNEXdegp") = "Deg/sec"


' Angular Displacement

Call FormulaCalc("ch('[1]/SPNEXdegpM'):= ch('[1]/SPNEXdegp')*9.80665")' g -> M/sec^2

Call CHNINTEGRATE("[1]/Time","[1]/SPNEXdegpM","[1]/SPNEXdegp_Dis")

ChnDim("[1]/SPNEXdegp_Dis") = "Deg"

Call CHNDELETE("[1]/SPNEXdegpM")


' Y


Call
CHNCFCFILTCALC("[1]/Time","[1]/SPNEYdeg","[1]/SPNEYdegp","CFC_60",0,"EndPoints",
10)

ChnDim("[1]/SPNEYdegp") = "Deg/sec"


' Angular Displacement

Call FormulaCalc("ch('[1]/SPNEYdegpM'):= ch('[1]/SPNEYdegp')*9.80665")' g -> M/sec^2

Call CHNINTEGRATE("[1]/Time","[1]/SPNEYdegpM","[1]/SPNEYdegp_Dis")

ChnDim("[1]/SPNEYdegp_Dis") = "Deg"

Call CHNDELETE("[1]/SPNEYdegpM")


' Z
```

```
Call CHNCFCFILTCALC("[1]/Time","[1]/SPNEZdeg","[1]/SPNEZdegp","CFC_60",0,"EndPoints",10)

ChnDim("[1]/SPNEZdegp") = "Deg/sec"


' Angular Displacement

Call FormulaCalc("ch('[1]/SPNEZdegpM'):= ch('[1]/SPNEZdegp')*9.80665")' g -> M/sec^2

Call CHNINTEGRATE("[1]/Time","[1]/SPNEZdegpM","[1]/SPNEZdegp_Dis")

ChnDim("[1]/SPNEZdegp_Dis") = "Deg"

Call CHNDELETE("[1]/SPNEZdegpM")




' Delete raw data channels

Call CHNDELETE("[1]/RAMXD")

Call CHNDELETE("[1]/RAMPSI")

Call CHNDELETE("[1]/RAMXG")

Call CHNDELETE("[1]/RAMFX")

Call CHNDELETE("[1]/RAMFY")

Call CHNDELETE("[1]/RAMFZ")

Call CHNDELETE("[1]/RAMMX")

Call CHNDELETE("[1]/RAMMY")

Call CHNDELETE("[1]/RAMMZ")
```

e. Data Analysis MATLAB Script

```
%%  Geoff Brown

 %  Data Analysis Script

 %  Denuded Thorax Impact Project

 %  Undergraduate Research

 %  IBRL  --  John Bolte


 clear all;

 clc;

%% Data Input

load('one_1.txt');

load('one_2.txt');

load('one_3.txt');

load('one_4.txt');

load('two_1.txt');

load('two_2.txt');

load('two_3.txt');

load('two_4.txt');

one_5=one_4;

one_4=one_3;


Time1=one_1(:,2);Time2=one_2(:,2);Time3=one_4(:,2);Time4=one_5(:,2);

Time5=two_1(:,2);Time6=two_2(:,2);Time7=two_3(:,2);Time8=two_4(:,2);

stgage1=one_1(:,(11:19));stgage2=one_2(:,(11:19));

stgage3=one_4(:,(11:19));stgage4=one_5(:,(11:19));

stgage5=two_1(:,(11:19));stgage6=two_2(:,(11:19));

stgage7=two_3(:,(11:19));stgage8=two_4(:,(11:19));
```

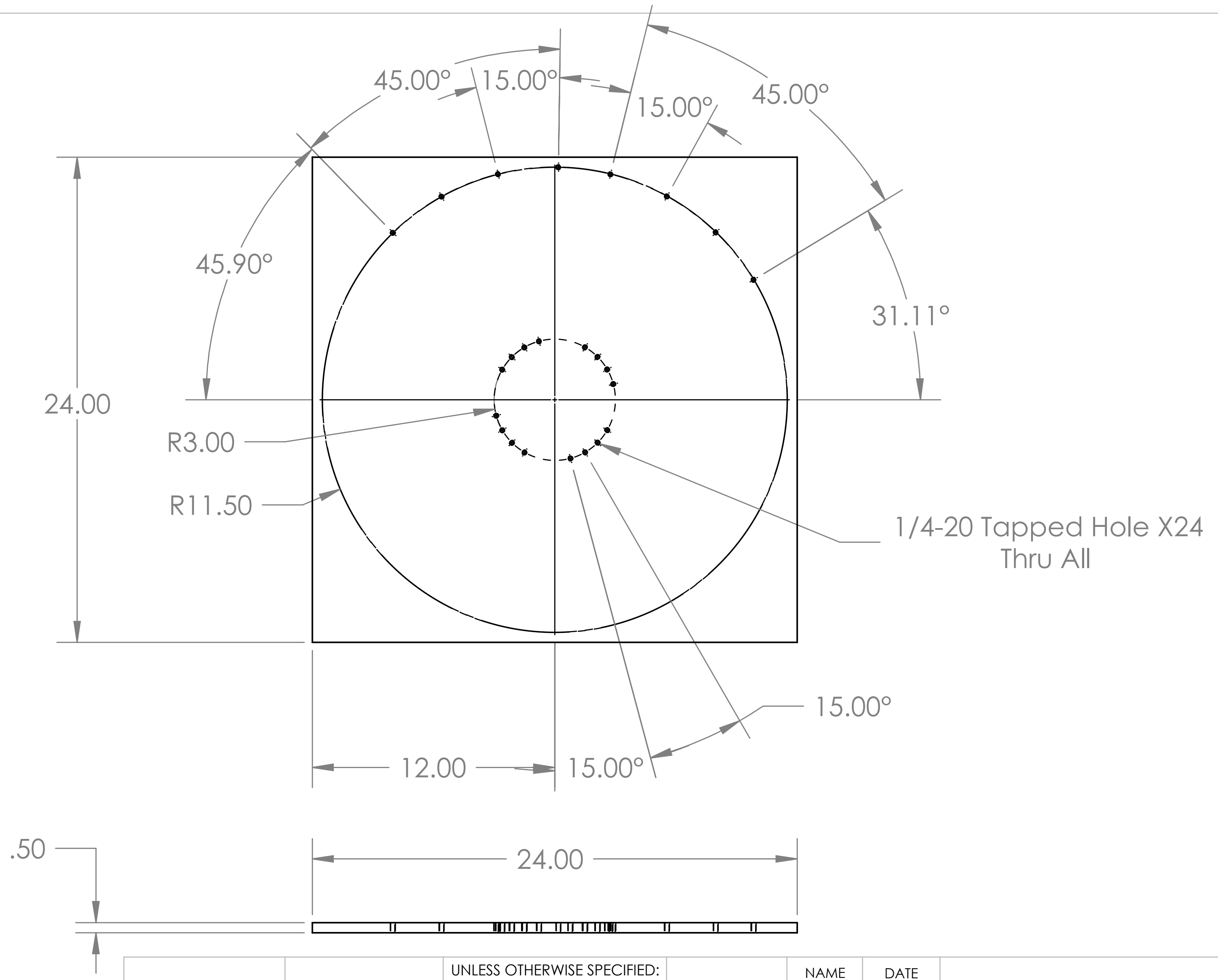
```
ramf1=one_1(:,31);ramf2=one_2(:,31);ramf3=one_4(:,31);
ramf4=one_5(:,31);ramf5=two_1(:,31);ramf6=two_2(:,31);
ramf7=two_3(:,31);ramf8=two_4(:,31);
ramd1=one_1(:,32);ramd2=one_2(:,32);ramd3=one_4(:,32);
ramd4=one_5(:,32);ramd5=two_1(:,32);ramd6=two_2(:,32);
ramd7=two_3(:,32);ramd8=two_4(:,32);
strnx1=one_1(:,(33:35));strnx2=one_2(:,(33:35));strnx3=two_1(:,(33:35));
strnx4=two_2(:,(33:35));
strny1=one_1(:,(36:38));strny2=one_2(:,(36:38));strny3=two_1(:,(36:38));
strny4=two_2(:,(36:38));
strnz1=one_1(:,(39:41));strnz2=one_2(:,(39:41));strnz3=two_1(:,(39:41));
strnz4=two_2(:,(39:41));
angx1=one_1(:,(42:43));angx2=one_2(:,(42:43));angx3=two_1(:,(42:43));
angx4=two_2(:,(42:43));
angy1=one_1(:,(44:45));angy2=one_2(:,(44:45));angy3=two_1(:,(44:45));
angy4=two_2(:,(44:45));
angz1=one_1(:,(46:47));angz2=one_2(:,(46:47));angz3=two_1(:,(46:47));
angz4=two_2(:,(46:47));

%% Strain Gage Plots
figure(1)
plot(Time1,stgage1(:,(1:8)), Time5,stgage5)
xlabel('Time (s)');ylabel('[mV]');
Title('Oblique Impact/Unrestrained Sternum')

figure(2)
plot(Time2,stgage2, Time6,stgage6)
```

```
xlabel('Time (s)');ylabel('[mV]');

Title('Lateral Impact/Unrestrained Sternum')


figure(3)

plot(Time3,stgage3, Time7,stgage7)

xlabel('Time (s)');ylabel('[mV]');

Title('Oblique Impact/Restrained Sternum')


figure(4)

plot(Time4,stgage4, Time8,stgage8)

xlabel('Time (s)');ylabel('[mV]');

Title('Lateral Impact/Restrained Sternum')


%% Force and Force vs. Deflection


figure(5)

plot(Time1,ramf1,Time3,ramf3,Time5,ramf5,Time7,ramf7)

title('Oblique Impact Force')

xlabel('Time [s]')

ylabel('Force [N]')

legend('0801ODTH18LF01','0801ODTH18LR04','0802ODTH18LF01','0802ODTH18LR03',0)



figure(6)

plot(Time2,ramf2,Time4,ramf4,Time6,ramf6,Time8,ramf8)

title('Lateral Impact Force')
```

```
xlabel('Time [s]')
ylabel('Force [N]')
legend('0801LDTH18LF02','0801LDTH18LR05','0802LDTH18LF02','0802LDTH18LR04',0)

figure(7)
plot(ramd1,ramf1,ramd3,ramf3,ramd5,ramf5,ramd7,ramf7)
title('Oblique Force vs. Deflection')
xlabel('Deflection [mm]')
ylabel('Force [N]')
legend('0801ODTH18LF01','0801ODTH18LR04','0802ODTH18LF01','0802ODTH18LR03',0)



figure(8)
plot(ramd2,ramf2,ramd4,ramf4,ramd6,ramf6,ramd8,ramf8)
title('Lateral Force vs. Deflection')
xlabel('Deflection [mm]')
ylabel('Force [N]')
legend('0801LDTH18LF02','0801LDTH18LR05','0802LDTH18LF02','0802LDTH18LR04',0)

%% Angular Displacement/Velocity

figure(9)
plot(Time1,angx1(:,1),Time2,angx2(:,1),Time5,angx3(:,1),Time6,angx4(:,1))
title('X-axis Rotation')
xlabel('Time [s]')
ylabel('Angular Velocity [deg/s]')
```

```
legend('0801ODTH18LF01','0801LDTH18LF02','0802ODTH18LF01','0802LDTH18LF02',0)


figure(10)

plot(Time1,angy1(:,1),Time2,angy2(:,1),Time5,angy3(:,1),Time6,angy4(:,1))

title('Y-axis Rotation')

xlabel('Time [s]')

ylabel('Angular Velocity [deg/s]')

legend('0801ODTH18LF01','0801LDTH18LF02','0802ODTH18LF01','0802LDTH18LF02',0)


figure(11)

plot(Time1,angz1(:,1),Time2,angz2(:,1),Time5,angz3(:,1),Time6,angz4(:,1))

title('Z-axis Rotation')

xlabel('Time [s]')

ylabel('Angular Velocity [deg/s]')

legend('0801ODTH18LF01','0801LDTH18LF02','0802ODTH18LF01','0802LDTH18LF02',0)


figure(12)

plot(Time1,angx1(:,2),Time2,angx2(:,2),Time5,angx3(:,2),Time6,angx4(:,2))

title('X-axis Rotational Displacement')

xlabel('Time [s]')

ylabel('Displacement [deg]')

legend('0801ODTH18LF01','0801LDTH18LF02','0802ODTH18LF01','0802LDTH18LF02',0)


figure(13)

plot(Time1,angy1(:,2),Time2,angy2(:,2),Time5,angy3(:,2),Time6,angy4(:,2))

title('Y-axis Rotational Displacement')
```

```
xlabel('Time [s]')

ylabel('Displacement [deg]')

legend('0801ODTH18LF01','0801LDTH18LF02','0802ODTH18LF01','0802LDTH18LF02',0)


figure(14)

plot(Time1,angz1(:,2),Time2,angz2(:,2),Time5,angz3(:,2),Time6,angz4(:,2))

title('z-axis Rotational Displacement')

xlabel('Time [s]')

ylabel('Displacement [deg]')

legend('0801ODTH18LF01','0801LDTH18LF02','0802ODTH18LF01','0802LDTH18LF02',0)
```



		NAME	DATE
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COMMENTS:

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FRACTIONAL ±
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TITLE:

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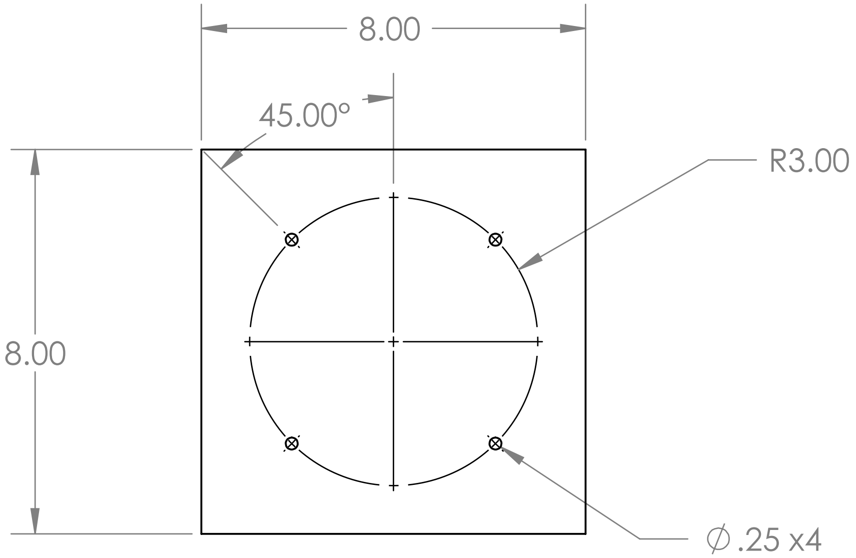
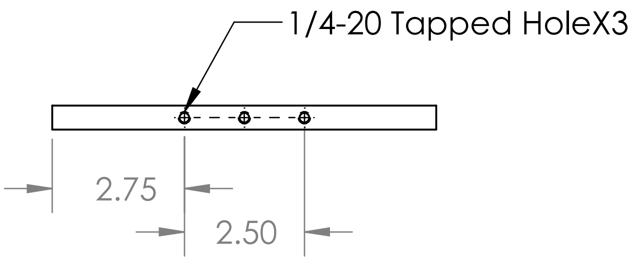
SCALE: 1:8
WEIGHT:
SHEET 1 OF 1

5 4 3 2 1





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	NAME	DATE
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COMMENTS:

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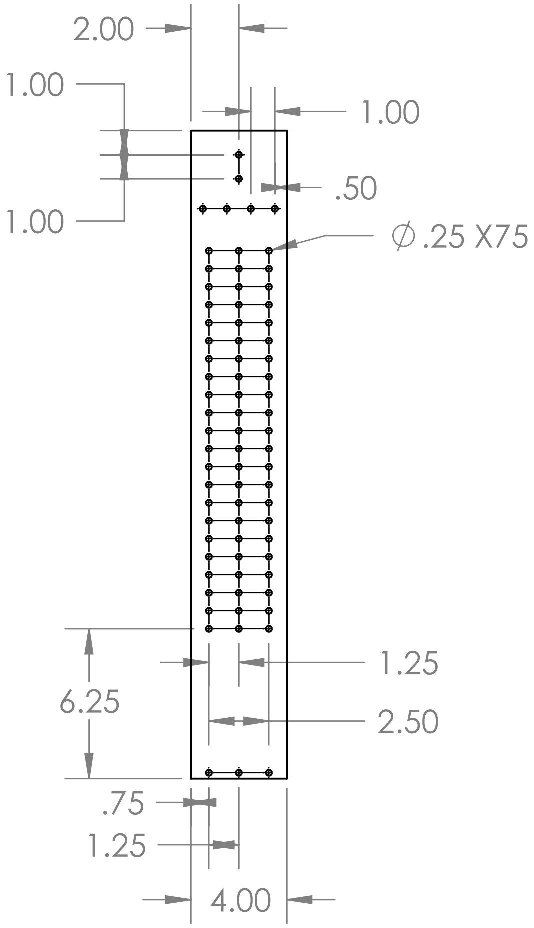
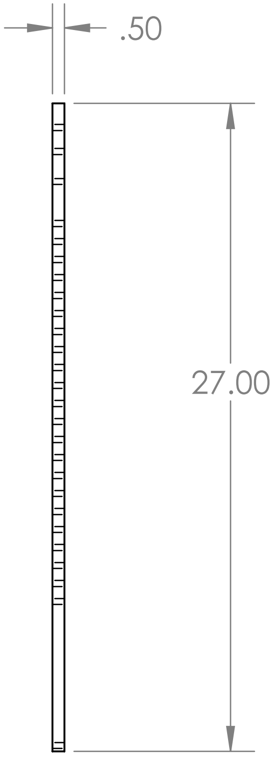
bottom
REV

SCALE: 1:4
WEIGHT:
SHEET 1 OF 1

5 4 3 2 1





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APPLICATION	

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FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
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ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE	DWG. NO.	REV
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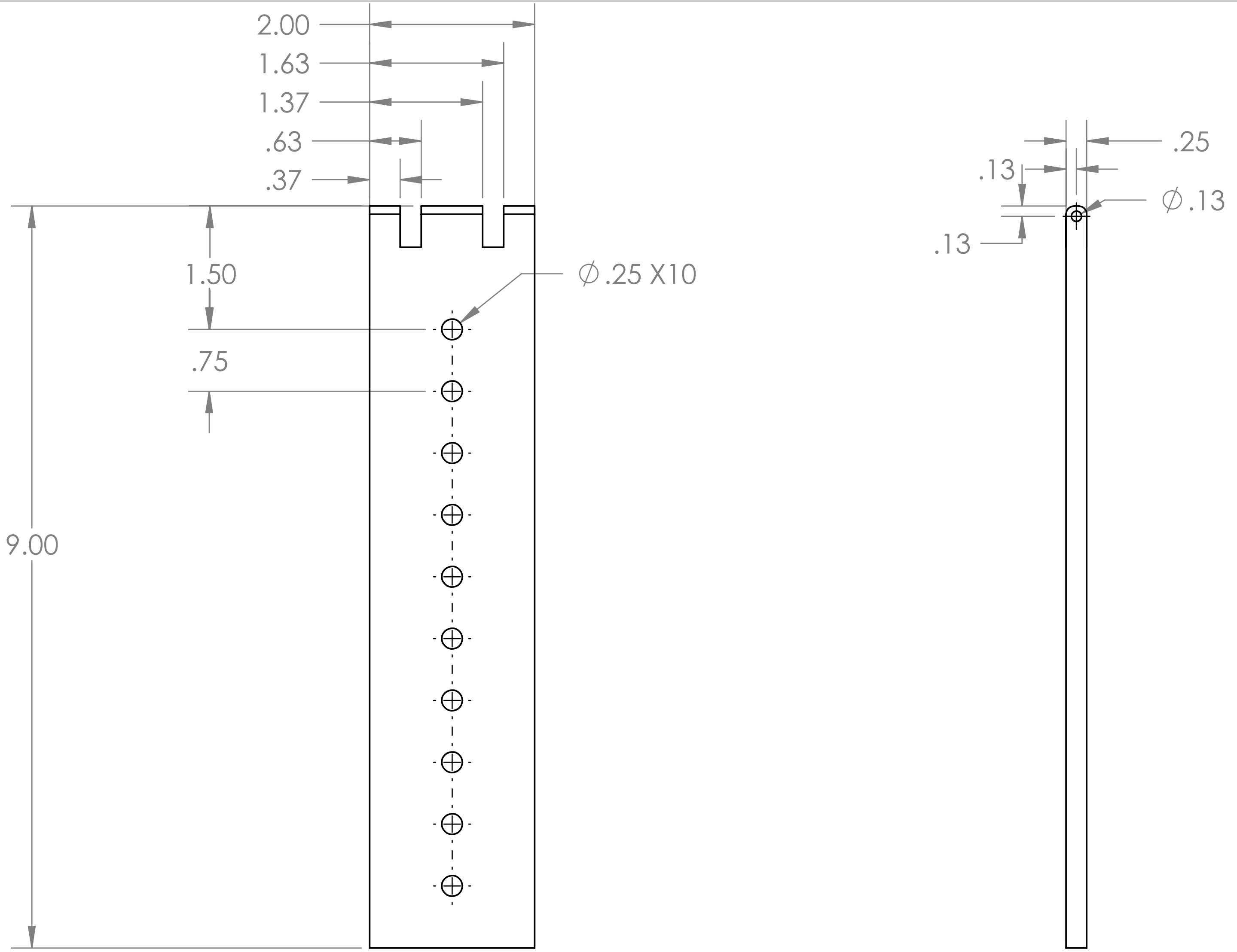
SCALE: 1:8 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



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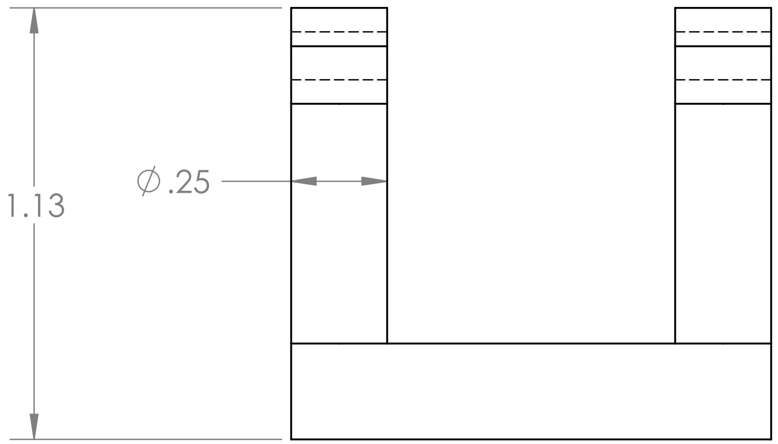
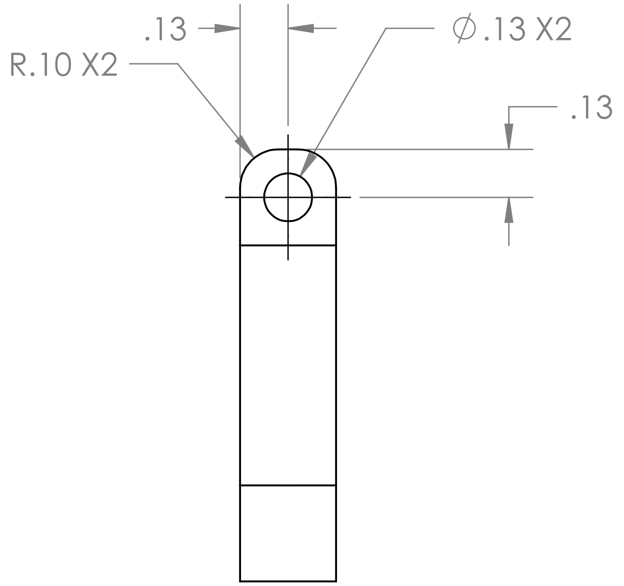
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

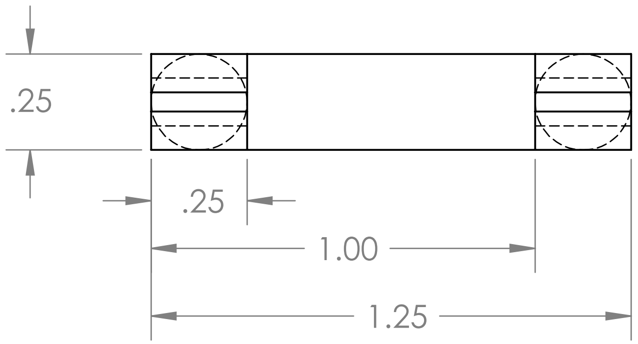
TITLE:

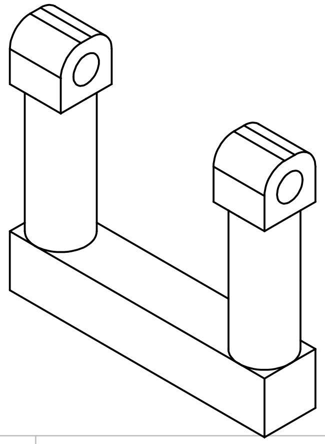
SIZE	DWG. NO.	REV
A	hinge_bot	
SCALE: 1:2	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1









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		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
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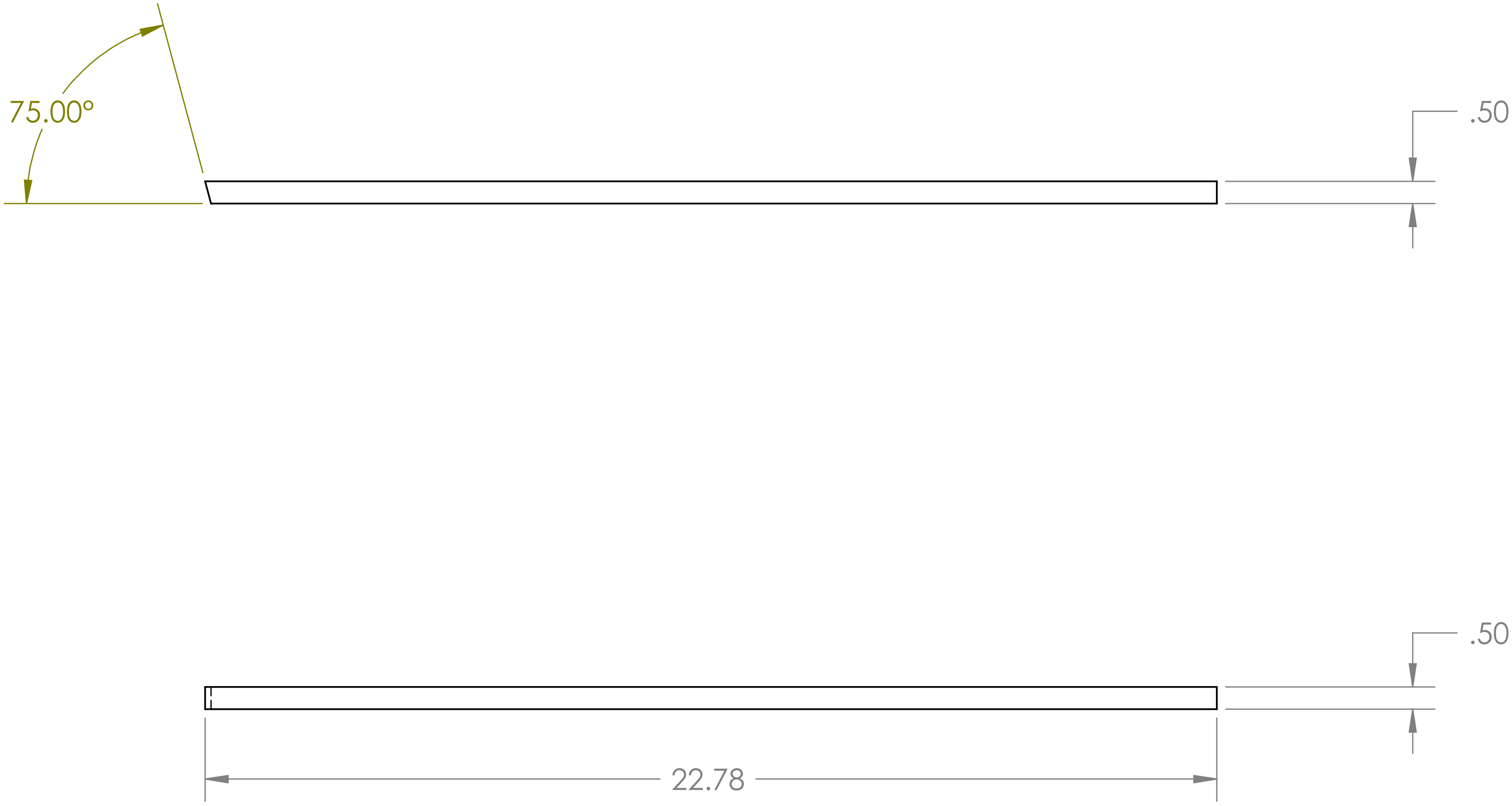
TITLE:

SIZE	DWG. NO.	REV
A	hinge_top	

SCALE: 2:1	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



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ANGULAR: MACH ± BEND ±
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MFG APPR.		
Q.A.		

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TITLE:

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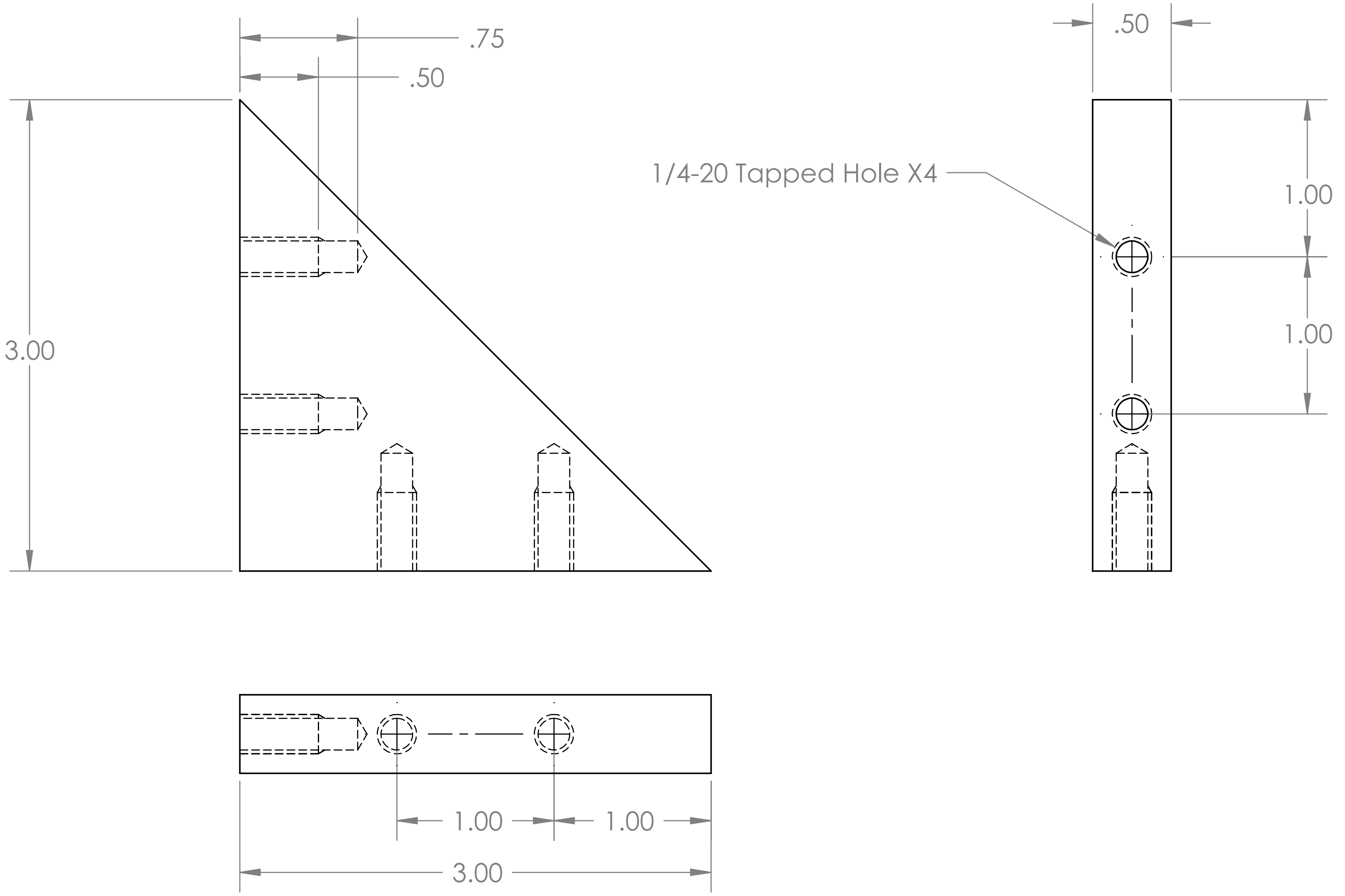
SCALE: 1:4 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



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		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
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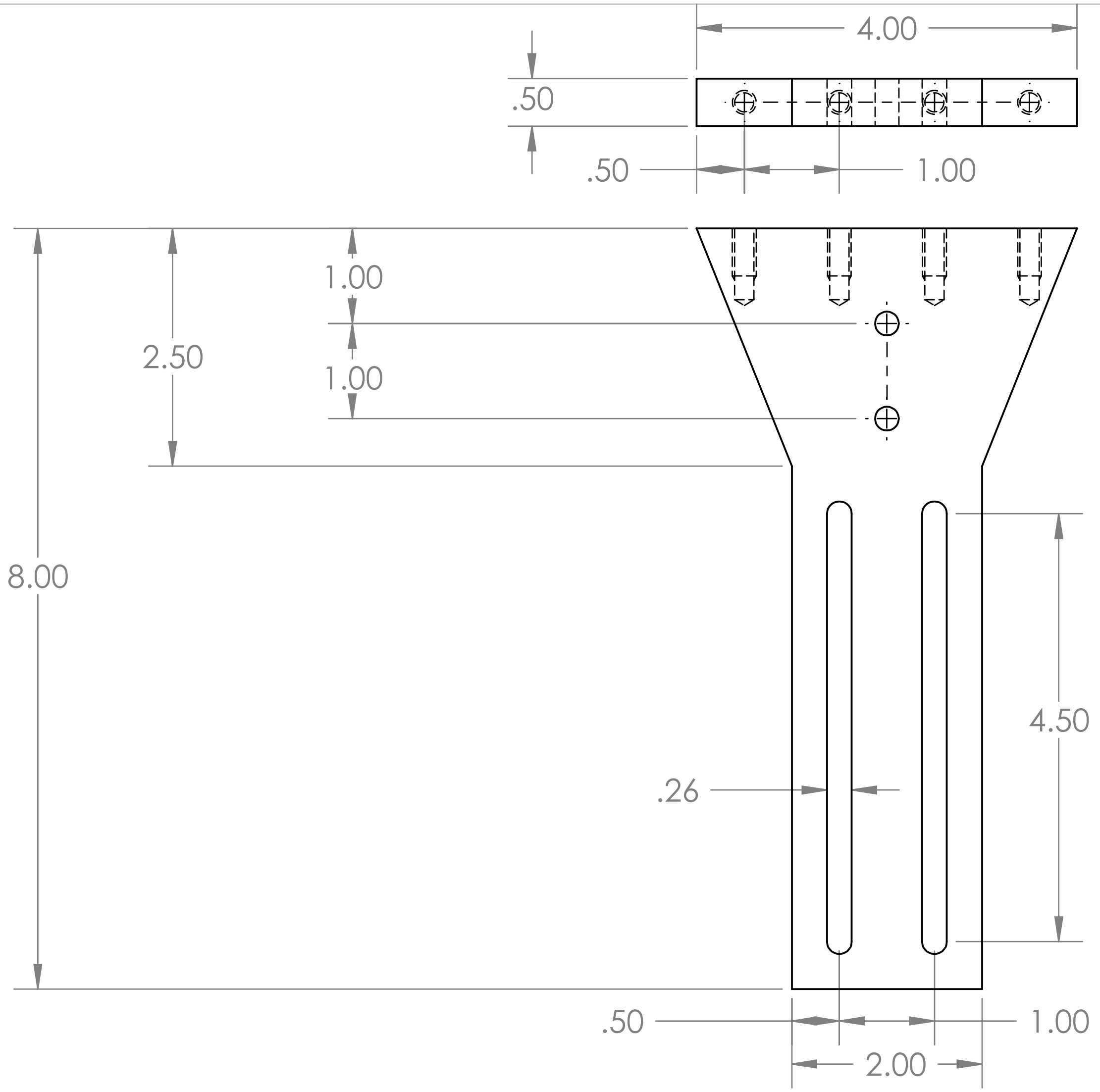
SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



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		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
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TITLE:

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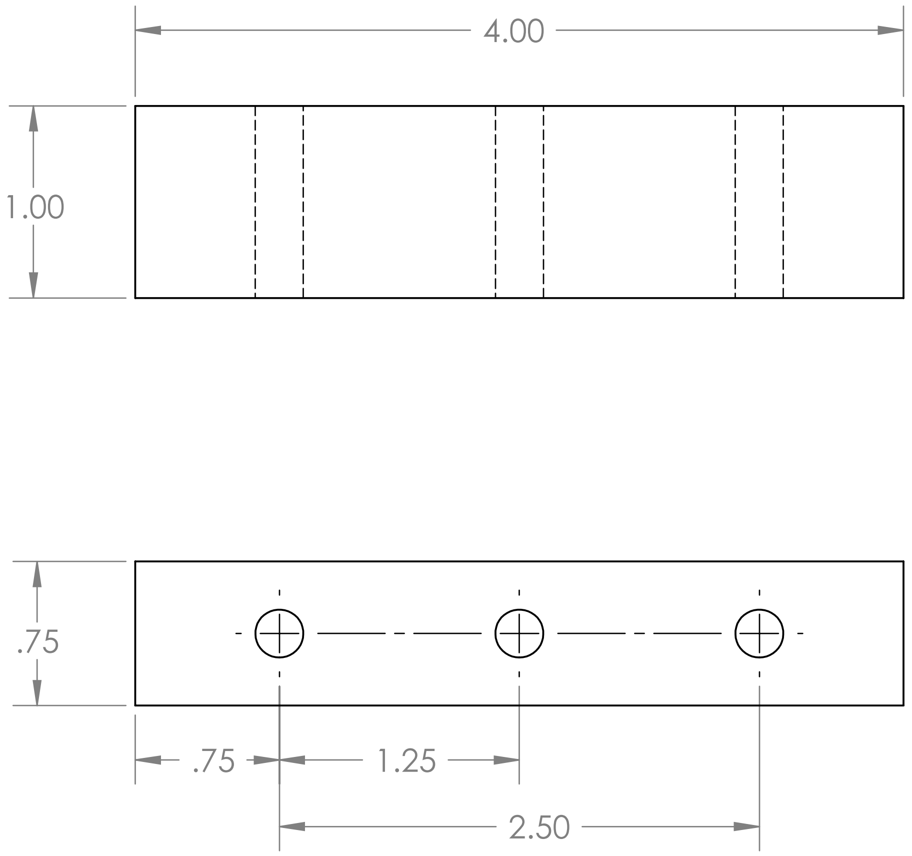
SCALE: 1:2 WEIGHT: SHEET 1 OF 1



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ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

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	NAME	DATE
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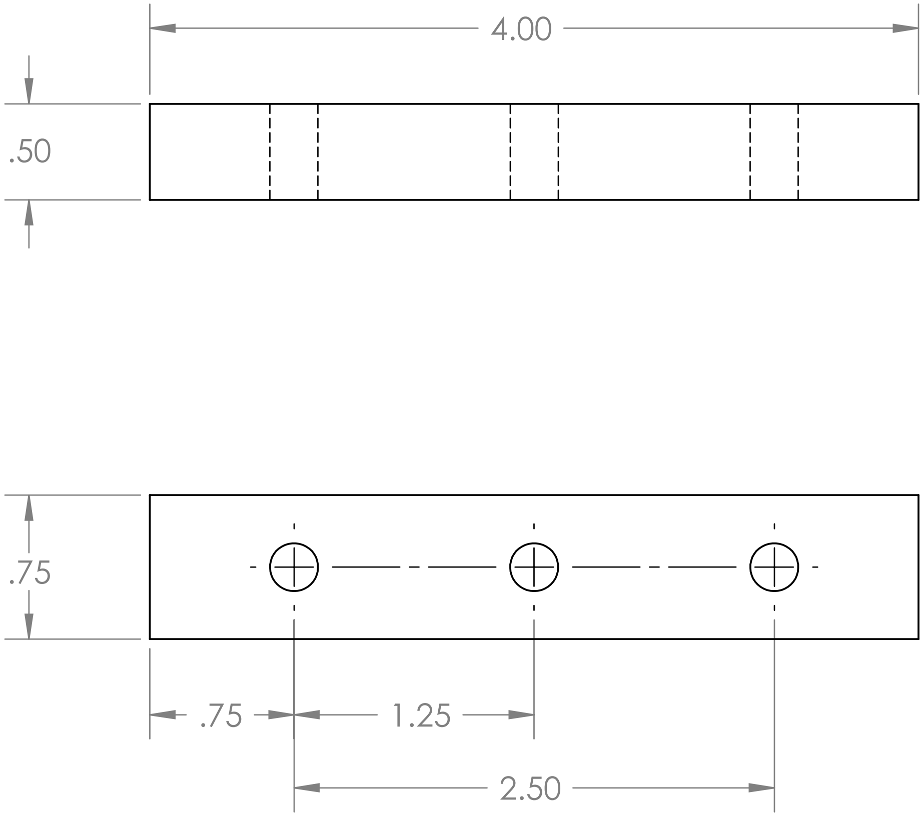
SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



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TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
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MFG APPR.		
Q.A.		

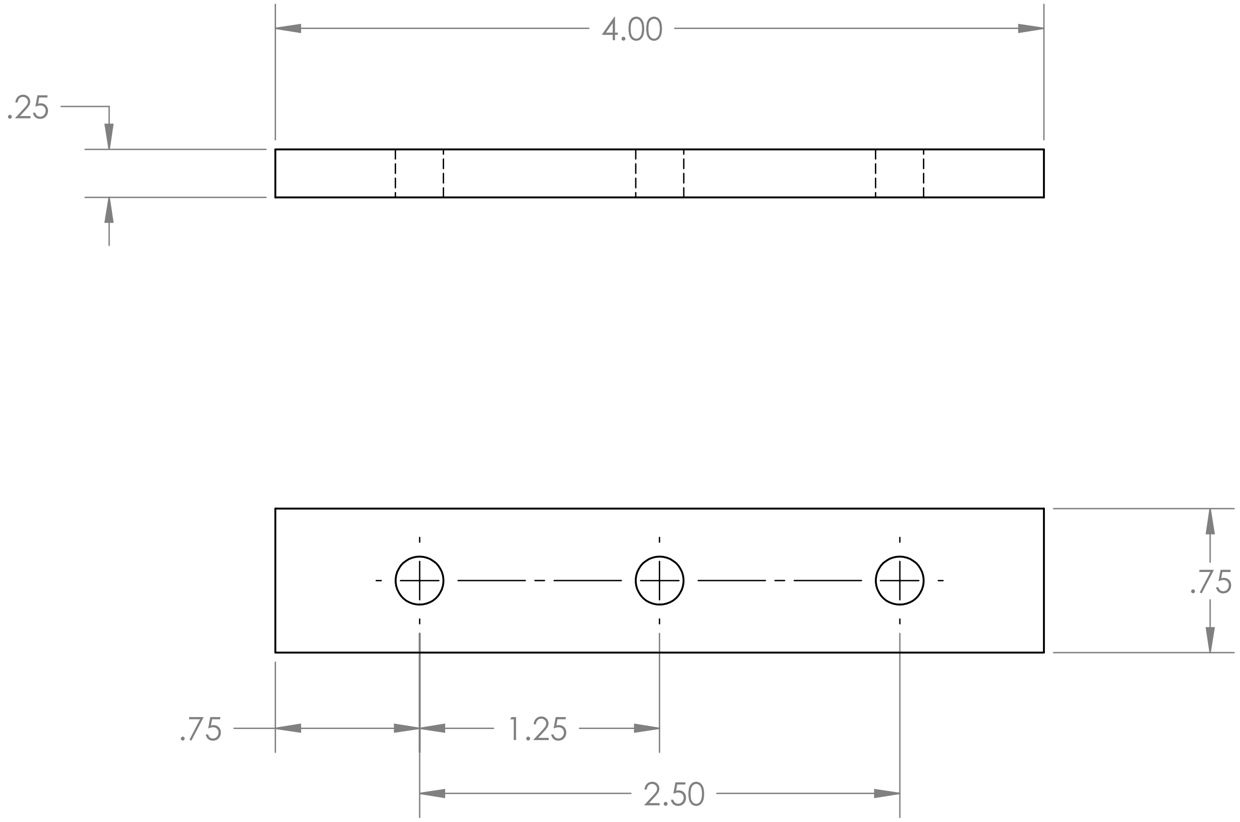
COMMENTS:

TITLE:

SIZE	DWG. NO.	REV
A	spacer_2	

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



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TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
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ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE
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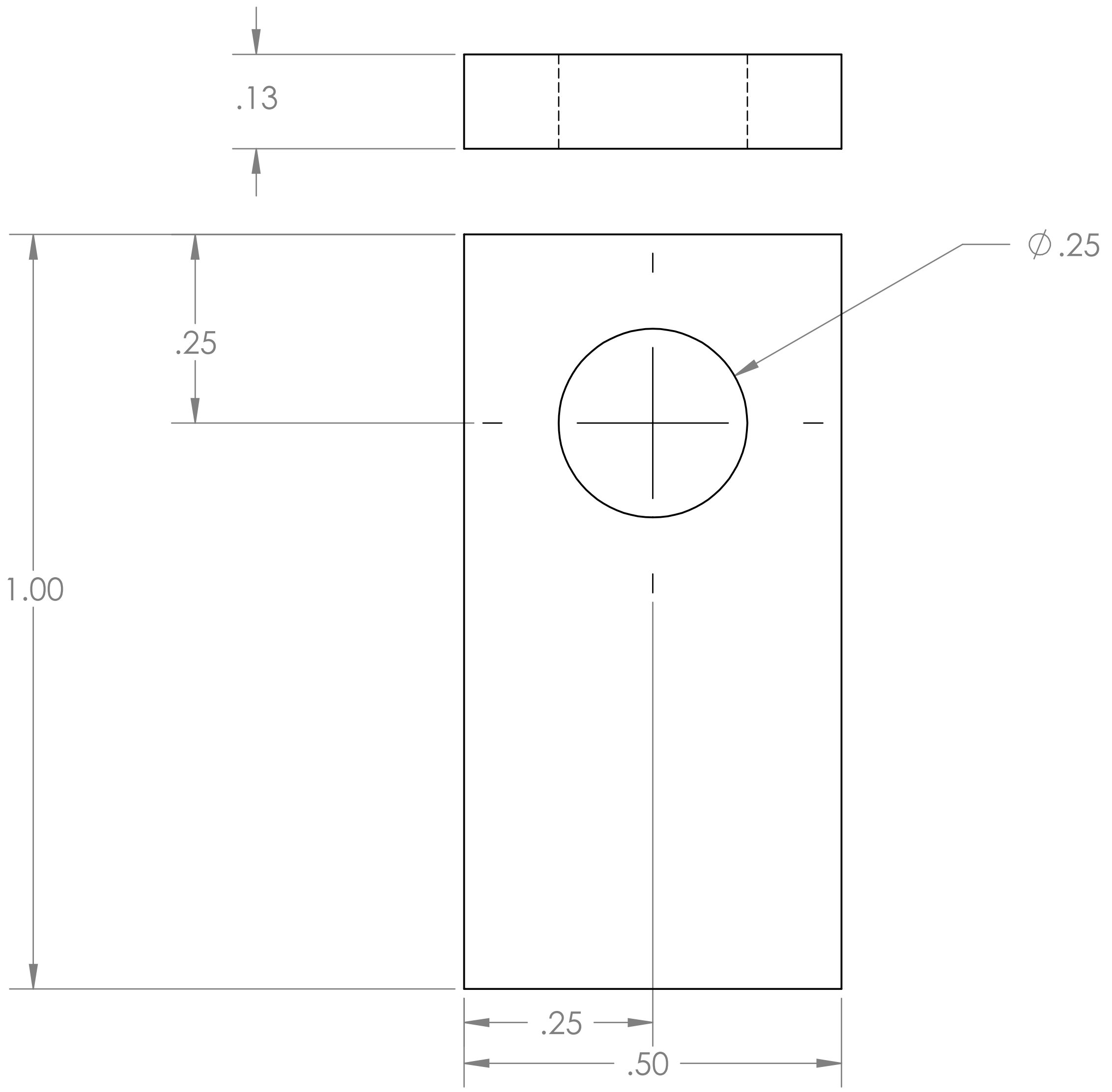
REV

SCALE: 1:1
WEIGHT:
SHEET 1 OF 1

5 4 3 2 1



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TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

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MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
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MFG APPR.		
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COMMENTS:

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SIZE	DWG. NO.	REV
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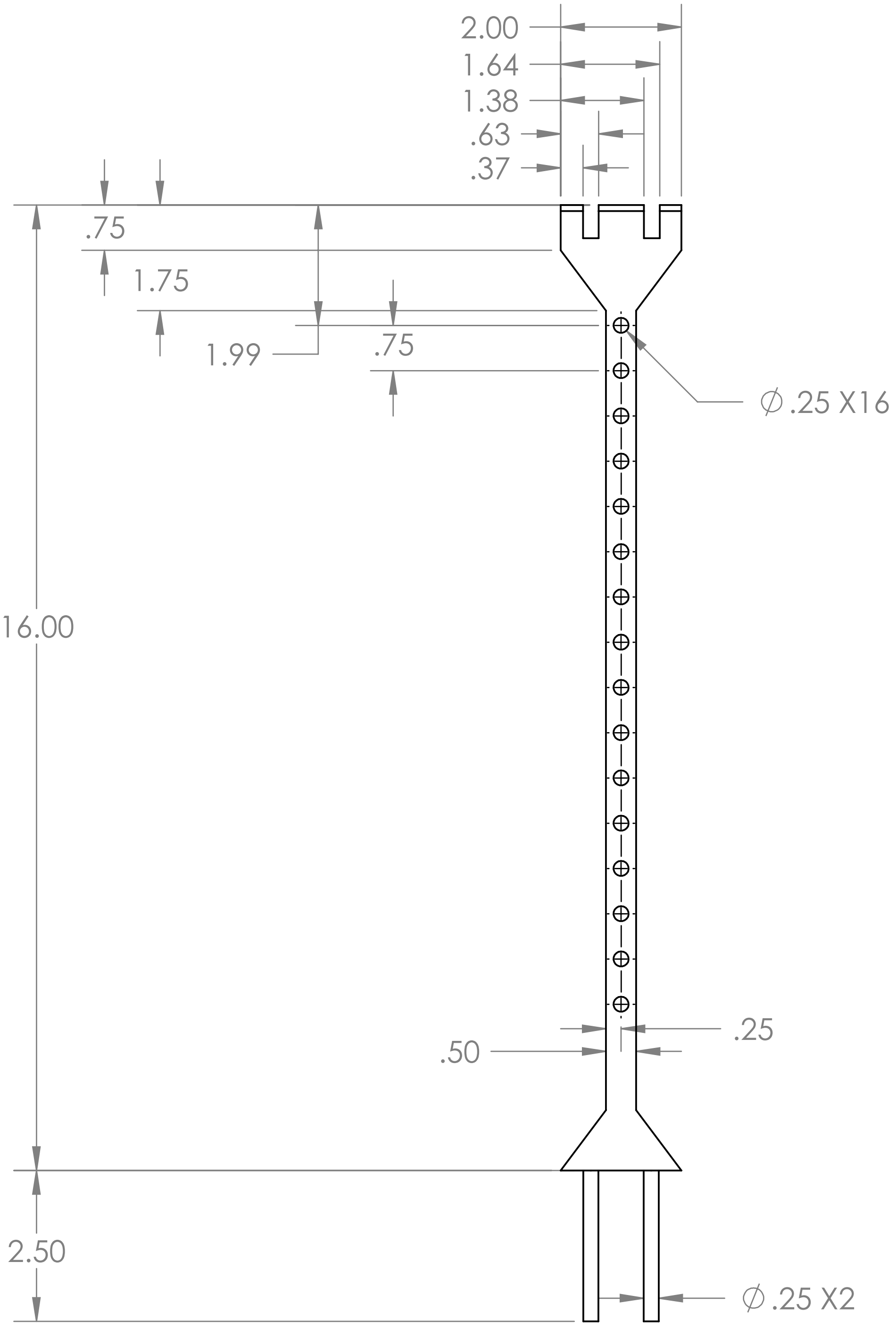
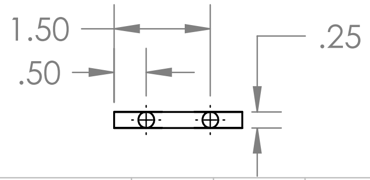
SCALE: 4:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1





DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±		NAME	DATE	
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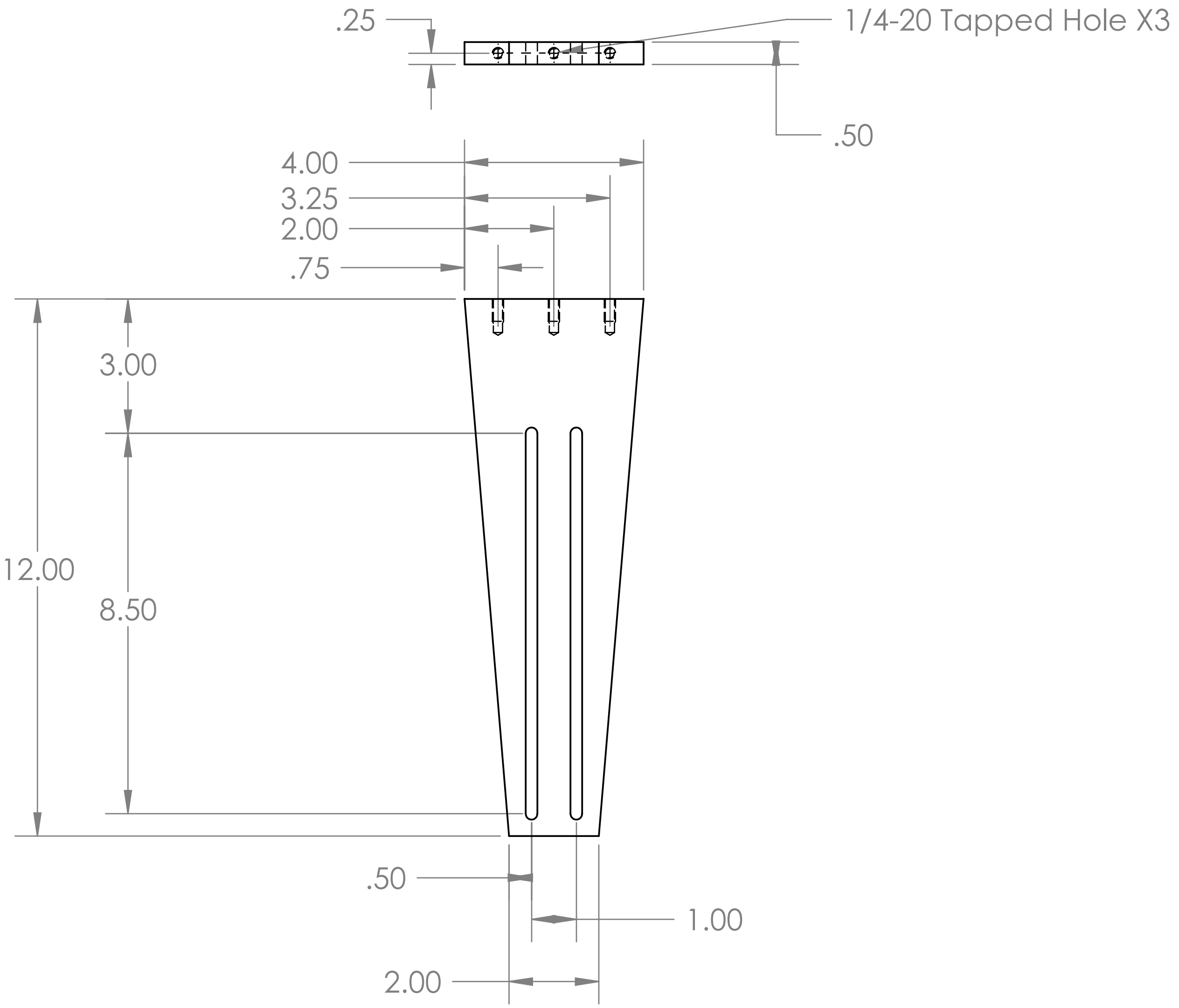
MATERIAL	Q.A.			
FINISH	COMMENTS:			
DO NOT SCALE DRAWING				

NEXT ASSY	USED ON
APPLICATION	

SIZE	DWG. NO.	REV.
A	hinge_bot2	

SCALE:1:1 WEIGHT: SHEET 1 OF 1



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TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

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APPLICATION	

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SCALE: 1:4 WEIGHT: SHEET 1 OF 1